TNO-report
TM-97-B004

title
The role of communication and coordination in team decision making in a command & control task

TNO Human Factors
Research Institute

Kampweg 5
P.O. Box 23
3769 ZG Soesterberg
The Netherlands

Phone +31 346 35 62 11
Fax +31 346 35 39 77

authors
W.M. Post
P.C. Rasker
J.M.C. Schraagen

date
13 May 1997

number of pages : 53 (incl. appendices, excl. distribution list)

TNO Human Factors Research Institute is part of TNO Defence research to which also belong:
TNO Physics and Electronics Laboratory
TNO Prins Maurits Laboratory

Netherlands Organization for Applied Scientific Research

Management uittreksel TNO Technische Menskunde, Soesterberg

titel:	De rol van communicatie en coördinatie bij teambesluitvorming in een command & control taak
auteurs:	Dr. W.M. Post, drs. P.C. Rasker en dr. J.M.C. Schraagen
datum:	13 mei 1997
opdrachtnummer:	B97-021
IWP-nummer:	787.2
rapportnummer:	TM-97-B004

In deze studie is de rol van communicatie en coördinatie bij teambesluitvorming onderzocht. Hiervoor is eerst een raamwerk ontwikkeld waarin aan een team gerelateerde entiteiten zijn vervat. Dit raamwerk beschrijft dat een organisatie die haar doelen wil bereiken te maken heeft met haar omgeving. De organisatie moet voor het realiseren van haar doelen werk verzetten waarvoor zij middelen als agenten, machines en gereedschappen tot haar beschikking heeft. Wanneer een enkele agent niet over voldoende kennis en capaciteiten beschikt om het benodigde werk te verzetten zal een multi-agent systeem worden gevormd.

Een voorbeeld van zo'n multi-agent systeem is een team. Om de kennis en capaciteiten van de teamleden te combineren moet het team communiceren en coördineren, wat overhead vereist en een bron van fouten kan zijn. Problemen met team communicatie en coördinatie kan tot desastreuze gevolgen leiden in situaties waar levens op het spel staan.

Om de rol van communicatie en coördinatie te onderzoeken hebben we een kunstmatige wereld ontwikkeld waarin verschillende gebeurtenissen plaatsvinden. Deze wereld wordt gerepresenteerd door een stad die bestaat uit verscheidende gebouwen waarin zich burgers bevinden. De gebeurtenissen bestaan uit een serie branden. Een brandweerorganisatie is opgezet om deze situatie het hoofd te bieden. De organisatie moet haar beperkte hoeveelheid middelen inzetten om haar doel te bereiken: het redden van zoveel mogelijk burgers.

Focus van het onderzoek is hoe een team samen te stellen en te ondersteunen dat de situatie observeert en beslissingen neemt over het gebruik van de middelen. Deze taken zijn in detail geanalyseerd en een normatieve taakstructuur is beschreven dat dienst deed als basis voor prestatie-metingen. Drie experimenten zijn uitgevoerd. Ten eerste werd de veronderstelling getoetst dat de experimentele taak niet goed door een enkeling kan worden uitgevoerd. Ten tweede werd onderzocht of een team met beperkte, maar voor de taakuitvoering voldoende, communicatie- en coördinatiemogelijkheden, even goed presteert als een team met onbeperkte mogelijkheden. Ten derde werd onderzocht wat de rol van kennisdistributie is.

Drie hoofdconclusies zijn getrokken. Ten eerste bleek dat cruciale taakelementen beter parallel kunnen worden uitgevoerd en de taak dus door een team moet worden uitgevoerd. Ten tweede kwam uit dat als communicatie beperkt wordt tot het uitwisselen van data dit de prestatie vermindert. Ten derde lieten de resultaten zien het distribueren van kennis over team leden tot een toename van parallelle taakuitvoering leidt en tot betere prestatie. Uit observaties kwam tenslotte naar voren dat bij vrije communicatie en coördinatie zowel tijdens als tussen het uitvoeren van taken veel kennis en veel taakinformatie wordt uitgewisseld.

Verder onderzoek richt zich op de ondersteuning van team coördinatie. Gebruikmakend van hetzelfde paradigma worden twee condities vergeleken. In beide condities zullen de teams beperkt kunnen communiceren en coördineren, maar in één conditie zal het team actief worden ondersteund in de prioritisering van de taken. Deze ondersteuning zal bestaan uit dynamische visualisatie van de taakafhankelijkheden tussen degene die observeert en degene die de middelen inzet. De hypothese is dat de uitwisseling van coördinatie-informatie de prestatie van teambesluitvorming verbetert.

CONTENTS Page

Report: TM-97-B004

Title: The role of communication and coordination in team decision making in a command & control task

Authors: W.M. Post, P.C. Rasker and J.M.C. Schraagen

Institute: TNO Human Factors Research Institute
Group: Information Processing

Date: May 1997

DO Assignment No.: B97-021

Number in Program of Work: 787.2

SUMMARY

In this study, the role of communication and coordination in team decision making in a command and control task has been investigated. First, a framework has been developed in which all team-related entities are described. Next, we have developed an artificial world in which various events take place. This world is represented by a city consisting of various buildings in which citizens live. The events are series of fires. A fire-fighting organization has been set up to deal with this situation. This organization has to allocate a restricted amount of resources to fulfill its goal: to rescue as many lives as possible.

Focus of research is on how to organize and support a team that observes the world and allocates the resources. These tasks have been analysed and a normative task structure has been described as a basis for performance measurements. Two experiments have been carried out. First, the hypothesis was tested that an experimental task (fire fighting) could not be carried out alone. Second, it was investigated whether teams that are restricted in their communication and coordination possibilities could perform as well as teams that can communicate and coordinate without restrictions. A third research topic was the role of distributing knowledge among the task performers.

The following three main conclusions can be drawn from the experimental results. First, the fire-fighting task truly is a team task because for optimal task performance, crucial task elements should be carried out in parallel. Second, communication restricted to data exchange only leads to team performance decrease. Third, distributing knowledge over team members leads to an increase of parallel task execution and to better team performance. Finally, we have observed that when team members can communicate without restrictions, much knowledge and information about the task is exchanged, both during and between the execution of tasks.

Rapport TM-97-B004

TNO Technische Menskunde
Soesterberg

De rol van communicatie en coördinatie bij teambesluitvorming in een command & control taak

W.M. Post, P.C. Rasker en J.M.C. Schraagen

SAMENVATTING

In deze studie is de rol van communicatie en coördinatie bij teambesluitvorming onderzocht. Hiervoor is eerst een raamwerk ontwikkeld waarin aan een team gerelateerde entiteiten zijn vervat. Vervolgens hebben we een kunstmatige wereld ontwikkeld waarin verschillende gebeurtenissen plaatsvinden. Deze wereld wordt gerepresenteerd door een stad die bestaat uit verscheidende gebouwen waarin zich burgers bevinden. De gebeurtenissen bestaan uit een serie branden. Een brandweerorganisatie is opgezet om deze situatie het hoofd te bieden. De organisatie moet haar beperkte hoeveelheid middelen inzetten om haar doel te bereiken: het redden van zoveel mogelijk burgers.

Focus van het onderzoek is hoe een team samen te stellen en te ondersteunen dat de situatie observeert en beslissingen neemt over het gebruik van de middelen. Deze taken zijn geanalyseerd en een normatieve taakstructuur is beschreven die dienst deed als basis voor prestatie-metingen. Drie experimenten zijn uitgevoerd. Ten eerste werd de veronderstelling getoetst dat de experimentele taak niet goed door een enkeling kan worden uitgevoerd. Ten tweede werd onderzocht of een team met beperkte, maar voor de taakuitvoering voldoende, communicatie- en coördinatiemogelijkheden, even goed presteert als een team met onbeperkte mogelijkheden. Ten derde werd onderzocht wat de rol van kennisdistributie is.

Drie hoofdconclusies zijn getrokken. Ten eerste bleek dat cruciale taakelementen beter parallel kunnen worden uitgevoerd en de taak dus door een team moet worden uitgevoerd. Ten tweede kwam naar voren dat als communicatie beperkt wordt tot het uitwisselen van data dit de prestatie vermindert. Ten derde lieten de resultaten zien dat het distribueren van kennis over team leden tot een toename van parallelle taakuitvoering leidt en tot betere prestatie. Uit observaties kwam tenslotte naar voren dat bij vrije communicatie en coördinatie zowel tijdens als tussen het uitvoeren van taken veel kennis en veel taakinformatie wordt uitgewisseld.

1 INTRODUCTION

1.1 Background

In most organisations, many jobs cannot be done alone, but have to be carried out in a team. The members of a team may differ in background, expertise and abilities. Many teams have to perform their tasks in complex work settings. Example teams are command & control teams, fire fighters, cockpit crews, and medical teams. The work setting of these teams may be characterized by time pressure, heavy work load, ambiguous information, and a constantly changing environment. Dysfunctioning of one or more members, or miscommunication among the team members, can lead to disastrous consequences. A major challenge is to find out how a team should cooperate to reach optimal performance under demanding circumstances. In particular, we are interested in determining the optimal conditions for a team to make decisions in critical situations.

Team decision making has received a great deal of attention in recent years (see, for example, Cannon-Bowers, Salas & Converse, 1993; Converse, Cannon-Bowers & Salas, 1991; Orasanu & Salas, 1993; Salas, Bowers & Cannon-Bowers, 1995). This interest of researchers is partly due to recent incidents which have demonstrated the importance of improving the performance of teams. For example, a commercial Iranian airliner was misidentified and shot down by the crew aboard the USS Vincennes. The crew misinterpreted the data and was consequently convinced that they were dealing with an attacking military aircraft. This example shows how poor team decision making can affect the lives of people. The research in this report was motivated by our interest in the factors involving team decision making. This in order to formulate recommendations for enhancing team performance and to prevent future accidents as a result of poor team decision making.

Before providing an overview of the literature on team decision making, we will first explain what we mean when we speak of a team. Dyer (1984) defined a team as follows:

> "A team consists of (a) at least two people, who are (b) working together towards a common goal/objective/mission, where (c) each person has been assigned specific roles or functions to perform, and where (d) completion of the mission requires some dependency among the group members" (p.286)

According to Orasanu and Salas (1993), the dependency among the members consists of information, knowledge, and means for reaching their common goal. Throughout this work, we will use the definition by Dyer and the further explication by Orasanu and Salas.

1.2 Goal

This work has multiple goals. First, we will try to define what constitutes a team by reviewing the literature on team decision making and by developing a framework for knowledge and

information used within a team. Second, we report on empirical research on team decision making that has been carried out in our institute. Third, we will formulate future research directions and a new research paradigm to improve our understanding of team decision making further. Our ultimate goal is to predict team performance as reliably as possible.

1.3 Research question

A team combines the knowledge and capacities of its members to deal with situations a single agent can not handle alone. A drawback of this is that team members have to communicate and coordinate their activities, which takes time, requires effort, and can be a source of errors. This work focuses on these two elements of team decision making. We are especially interested in the factors that play a role in team performance when team members have to communicate and coordinate under critical circumstances.

That effective communication and coordination can be vital in some situations was illustrated by the recent disaster with the Hercules military transport aircraft of the Belgian air force (see Duin & Rosenthal, 1996). During the landing at a Dutch airport, the Hercules got in trouble and crashed. Serious problems with communication and coordination arose when the emergency services provided their assistance. Normally, a load carrier plane like the Hercules contains a crew of four individuals. This time, however, the plane transported a brass band of the Dutch Royal Army consisting of 37 people. Although the air-traffic controller knew that people were transported, this information was not distributed or was misunderstood by the emergency services. Consequently, the emergency services allocated less resources than necessary and were interested in the cockpit instead of the rear end of plane where the transported people were seated. When the kind of load would have been known by the emergency services from the beginning, a different strategy would have been adopted and probably more lives could have been saved.

Although accurate communication is of great importance, it is just a part of the picture. In rapidly changing situations teams may have to cope with ambiguous information or information that is out of date. Moreover, in non-routine and new situations it even may be not clear which information can be perceived as useful. On top of this, communication does not merely serves a function of distributing accurate data information (i.e., information needed to complete the task such as the number of casualties in the Hercules incident) but also a function of coordination and correction. An important function that is served by communication is the possibility to monitor and correct ongoing activities. This is known as team-self correction and can be seen as a specific extension on the traditional feedback concept. According to Blickensderfer, Cannon-Bowers and Salas (in press) "it is contented that intra-team feedback (i.e., members giving each other feedback regarding how they are performing the task and their underlying expectations for performance), can help to foster correct expectations and intentions among team members and also facilitate modifications of incorrect expectation and intentions". When in the Hercules case the air-traffic controller

would have had information about how the emergency services coordinated their actions, he could have inferred that they had chosen the wrong strategy (i.e., to start at the cockpit in stead of the rear end; and using a restricted amount of resources).

Rouse, Cannon-Bowers and Salas (1992) suggest that effective coordination and communication within teams depends on correct expectations and interpretations of what others will do. In other words, in a well coordinated team, members hold accurate expectations of each others tasks and activities. Furthermore, team members also have an accurate interpretation of this. Holding the right expectations and interpretations gives team members the opportunity to anticipate each others activities and provide essential information when necessary. This results in what Serfaty, Entin and Volpe (1993) call "implicit coordination". In sum, self monitoring of teams foster the development of adequate expectations of each others tasks and activities. On the basis of these expectations, teams can coordinate and communicate efficiently. Both Blickensderfer et al. as well as Rouse et al. elaborate their view of developing accurate expectations to the shared mental model concept. They suggest that this concept can be used as a framework that gives an explanation how people develop compatible expectations and interpretations of each other and the task.

When members of a team share knowledge from the outside world (whether or not as part of a shared mental model), a team as a whole may be less susceptible to inaccuracies. Team members can fill in each others deficiencies and correct their shortcomings. Also team members can substitute for each others tasks. This way activities of individual team members may be smoothly coordinated. In particular, shared knowledge can be useful in situations where communication among team members is not optimal. Redundancy in knowledge among different agents within a team can compensate for such situations because shared knowledge does not need to be communicated. This has been well illustrated with the Hercules disaster. If the knowledge about the number of passengers was shared among all participants, problems with the assistance probably could have been prevented.

Although shared knowledge can partly compensate for non-optimal communication, this may not be realizable in all situations. This is, for example, when members of a team have at their disposal highly specialized knowledge that takes years of training to acquire. Besides that, shared knowledge cannot be tested on its correctness when team members do not monitor each others knowledge. Especially in rapidly changing situations shared knowledge may soon be out of date. When people monitor this disagreement between the situation and their knowledge they have the opportunity to correct and adjust their knowledge. As in the case with the Hercules it is not very likely that all participants knew the number of passengers before the plane crashed. In other words, altogether sharing certain knowledge among team members may enhance coordination (and as a result performance levels), it is not applicable in every situation. Therefore we expect that, apart from shared knowledge that contributes to the overall team performance, team performance will be further improved when team members have the possibility of self-monitoring and self-correction.

According to Zsambok (1997) "many researchers agree that good teams monitor their performance and self-correct; offer feedback; maintain awareness of rules and functions and take action consistent with that knowledge; adapt to changes in the task or the team; communicate effectively; converge on a shared understanding of their situation and course of action; anticipate each other's actions or needs; and coordinate their actions" (p.112). The problem is, however, that these factors are intuitively appealing but need to be empirically tested. The research described in this report provides an experimental environment which can be used to investigate systematically certain factors of communication and coordination. Our main objective is to compare teams with full possibilities for communication with fewer possibilities for communication. In both situations, however, teams have the possibility to communicate the necessary information for an optimal performance.

Before we address the factors concerning the communication in teams, we would like to demonstrate that some tasks are so demanding that more than one agent is needed to perform the task. Primarily, this serves as a verification that the experimental task used really is a team task. Therefore the first question we want to investigate is:

Can we show the necessity of performing certain tasks by more than one agent?

Second, we want to demonstrate that when team members are restricted in their possibilities to communicate (i.e., no communication concerning task and domain knowledge, thus, no opportunity for self-monitoring or coordination) performance declines. This, in spite of the fact that there are sufficient possibilities for communication in order to perform the task well. The following research question will be investigated:

Will unrestricted communication contribute to a better performance?

Third, we want to demonstrate that, even when team members are restricted in their possibilities to communicate, shared knowledge can partly compensate for this omission. The following research question will be investigated:

Will the possession of shared knowledge among team members contribute to a better performance?

In the next section, we will analyse what types of knowledge and information a team has to deal with.

2 TEAM KNOWLEDGE AND INFORMATION FRAMEWORK

What types of knowledge and information are used by a team and how are they processed? This is the main question that guides our review of the literature on team decision making presented in this section.

An often used concept in describing team functioning is *Shared Mental Model* (Orasanu, 1993; Orasanu & Salas, 1993). This concept is based on the mental model concept. By this is meant "[...] the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and

predictions of future system states" (Rouse & Morris, 1986, p.351). Agents use mental models to describe the purpose and form of a system, to explain a system in terms of its functions and its state (what it is doing), and predicting a future state.

A *shared* mental model represents the intersection of the mental models of at least two individual agents. Orasanu and Salas (1993) include shared understanding of the problem, goals, information cues, strategies, and member roles in these models. They argue that this shared mental model is important for team decision making in order to enable team members to cooperate optimally. By using a shared mental model, a team would know how to coordinate its actions and what to communicate among the members of the team.

A related concept to shared mental model is *team mind* (Orasanu & Salas, 1993), which refers to shared information processing capabilities, especially memory encoding, storage and retrieval. Each team member knows what problem information and what expertise other members have. In this way, the individual knowledge and information storage capacity is expanded. According to Orasanu & Salas, shared mental models and team mind should be regarded as conceptual frameworks for research on teams making decisions rather than fully developed theories.

In addressing the mental models team members may have we will use five levels: the situation level (i.e., factors in the external environment of the team, such as the dynamics), the organisation level (e.g., work place, distance and time separation), the task level (the tasks that should be performed to realize organizational goals), the agent level (the performers of the tasks, who are limited in knowledge and capacity), the team level (the set of agents that carry out the tasks together, using knowledge about each others tasks, perform coordination and communication, etc.). We will use these layers to structure the overview of the literature.

2.1 Organizations are dealing with a situation

What is meant by situation. Organizations function within a context. For ship bridge personnel, this context consists of the environment (such as weather and current), the traffic, and the hydrography. For commercial organizations, elements of the situation are the market, the macro-economic situation, the competition, and technological developments. The external situation should be separated from the internal situation of the organization (such as resources, workplaces, etc.).

Non-determinism of the situation. The impact an organization can have on a situation can only be partial. Many actors and factors have an influence: competitors in the market, customer trends, adversaries. In other words, the influence on the situation is intrinsically unpredictable (Orasanu & Connolly, 1993). However, the impact of an organization on the situation can be estimated.

A difference exists between a situation and a situation description. There is a difference between the real external situation and how it is known to the organization. The external situation can only be described partially since the amount of information is too large to be captured or is impossible to obtain otherwise. And as with every description, problems can arise with the correctness, completeness, consistency of the description. One of the main tasks of an organization is keep the description as accurate as possible. But still, the situation is mostly described in terms of estimates, probabilities, etc. Describing explicitly what is unknown may be equally important. Rasmussen (1993) points out that decisions within an organization often should be based on partial external information. People are able to compensate and correct incomplete, unreliable and ambiguous information by means of a coherent mental model people have of the situation. According to Orasanu and Connolly (1993), available information about the situation may even be distorted intentionally, for example to mislead an adversary. Therefore, each part of a situation description that might have originated from an adversary should be regarded as suspect.

Dynamic situations, hectic situations. Another important characteristic of a situation, identified by many authors, is the dynamics of a situation (e.g., Rouse et al., 1992; Orasanu & Connolly, 1993). A situation can change rapidly, and so is the impact for the organization. The organization should be able to adapt quickly to a new situation, meaning that organizational goals, priorities and procedures may need revision. For example, the manning on the ship bridge should adapt their travel plan according to changing weather conditions. The time pressure under which a team may have to function may influence the functioning of a team importantly. The dynamic character of the situation gave rise to a lot of research, such as the TADMUS program (Tactical Decision Making Under Stress) (e.g., Rouse et al., 1992; Zachary, Zaklad, Hicinbothom & Ryder, 1993). This program was initiated after the command & control team of the USS Vincennes mistook an Iranian airliner for an aversive military plane. When the plane was within range to attack the ship, the team decided, within a time period of only minutes, to launch a missile in order to defend itself.

The impact of a changing situation. Not only the lack of time to make a decision induces stress, also the impact that a wrong decision may have. A mistake may lead to the fall of an enterprise, the discharge of the responsible people, or the unnecessary death of human beings, as has been the case in the Vincennes accident.

Naturalistic decision making. Aspects such as the uncertainty and dynamics of the situation, and the impact of a changing situation for the organization and their individuals, are some of the topics in a relatively new research paradigm, called naturalistic decision making (NDM, see e.g., Klein et al., 1993). The objective of NDM research is finding out how knowledge, experience, and skills are actually used in the decision making process in uncertain and demanding situations, as opposed to a normative approach of decision making.

The new paradigm brings together two problems. First, it is recognized that decision makers in practice do not apply probability theory and utility theory, in which options are generated

and weighted, and the best option is selected. Probability theory and utility theory are perfectly applicable in situations such as with gambles, when the situation is a standard one and sufficient time is available for the necessary calculations. The second problem with probability theory and utility theory is that the conditions may not change. Deciding, for example, to bet some money in a game such as roulette does not change the probability or utility of the outcome. However, it is often the objective to change the current situation. In that case, experience from previous situations, described by probabilities, is not useful since this experience is not applicable for the new situation. In addition, under new circumstances, other factors not known yet may have become important. An example of a changing situation in gambling is when the bank explodes: probability and utility theory do not work any more in that case.

Instead of calculating with probabilities, decision makers in actual practice recognize a situation as a familiar one, and act upon it in a standard way. Sometimes, when the situation is unfamiliar, they try to reason away the differences, and again use their standard repertoire. In other cases, when they are not convinced that their standard repertoire of action is appropriate, they can mentally simulate possible scenarios, in order to test and adapt the planned course of action (Klein, 1997).

How to describe the dynamics. Basically, the dynamics of a situation can be described in two different manners: process-based and event-based. In a process-based description, the situation is described after a fixed period of time. How much time will elapse between the points in time may depend on the effort needed to refresh the description and the possible situational change within that period of time. For describing process-based dynamics, only the notion of time is important (besides knowledge of how to recognize and describe the objects in the world).

In an event-based description, only qualitatively different situations are described. In this description a notion of what is "qualitatively different" is essential. This is determined by the activities, or tasks, that can be carried out to handle the event. As we will see below, these tasks are important for describing team functioning.

2.2 The organization

In contrast with the context of an organization, the organization itself can be controlled directly. An organization consists of resources that can be allocated and managed. These resources are the manpower of the organization, and means such as money and machines. Knowledge can be regarded as an organizational asset as well (see Post et al., 1997).

Goal and mission. The resources are used to reach a goal, or to fulfill a mission. A goal is usually formulated as a future situation the organization is aiming for; a mission as the process for reaching this goal. The mission of an organization is accomplished by means of

organizational functions. For a commercial organization, example functions are sales, production and research & development. For a ship, the functions are, for example, navigation, propulsion and lookout.

The future situation should be described in order to be known for the members of the organization. As with the description of a situation, the description can be incorrect, incomplete and inconsistent. Further, a goal is not static. It can change due to different external circumstances and the available resources (Orasanu & Connolly, 1993). For this reason, and for dealing with unforeseen situations, organizational flexibility is essential (Rouse et al., 1992).

Teams within an organization may function at a distance and asynchronously. Resources such as humans and machines consume time and space. Therefore, organizations have to structure their resources in work processes and workplaces. A design option for this structuring is to separate human resources in time and space. Working at a distance and asynchronously may have an impact on the functioning of the organization. Two decades ago, Chapanis, Parrish, Ochsman and Weeks (1977) investigated working at a distance via teletypewriters. Due to the technological developments on multimedia and telecommunications technology since, much research is carried out on computer communication, shared workspaces such as supported by conferencing systems, etc. (e.g., Fussell & Benimoff, 1995).

Organizational resources have to be compiled. The management and allocation of resources is one of the criteria that define a team (Salas, Dickenson, Converse & Tannenbaum, 1992). Adaptation of an organization to a changing situation (or changing goal situation) consists of the allocation of resources. When the organization is not able to cope with the demands of a situation, resources should be added (and withdrawn from a place in the organization where it is less needed). These resources may be human as well as machine power. The allocation of manpower is constrained, however. The number of members a team should consist of has an optimal size: when the number is too small, problems with backups may arise; when the number is too large, the overhead becomes a problem (see for example Mintzberg, 1983, for an account on organizational structures). In addition, the members of an organization need to get used to each other's ways, which takes time (Van Delft & Schuffel, 1995). For dynamic allocation, this start up time may take too long. Therefore, a permanent team may be installed which is oversized to be able to handle an incidental demanding situation.

2.3 Organizational goals are realized by performing tasks

Cannon-Bowers et al. (1993) explicitly incorporate tasks in their definition of shared mental models: "shared mental models are defined as knowledge structures held by members of a team that enable them to form accurate explanations and expectations for the task, and, in turn, to coordinate their actions and adapt their behaviours to the demands of the task and other team members" (p.228).

A model of team tasks is an essential part of a shared mental model. We define a task as "activities consuming time and effort in order to achieve a goal". The time element refers to the process in which tasks are realized; effort refers to the need for resources that provide the effort to carry out tasks. Three types of tasks can be distinguished: sensor tasks, motor tasks, and cognitive tasks.

Tasks are structured in processes. They can start and stop at any moment; run sequentially in a particular order or in parallel; they can be repeated, interrupted, etc. The structuring depends on the dependency between tasks: a particular task may not start before another task is completed.

The difference between function and task is the activity component. Functions are not defined in terms of activities, and therefore require no time and effort. Different types of tasks exist. Following Chandrasekaran (1987), a number of authors assume that complex tasks can be decomposed into a number of generic tasks. For military domains, Van Delft and Schuffel (1995) propose four main tasks: situation awareness, threat assessment, planning/decision making and direction & control. According to Adams (1995) the set of generic tasks are coordination, situation assessment, plan generation, and plan implementation. Van Heijst, Lanzola, Schreiber and Stefanelli (1994) use three similar basic tasks for the medical domain: diagnosis, therapy planning and patient monitoring. Hollingshead and McGrath (1995) distinguish the domain-independent tasks generate (creativity tasks, planning tasks), choose (intellective tasks, decision making tasks), negotiate (cognitive conflict tasks, mixed motive tasks), and execute (contests/competitive tasks, performance/psychomotor tasks).

2.4 Tasks are carried out by agents

Capacities. Tasks that realize functions are carried out by agents. Agents can be humans, machines, or software. For performing tasks, agents need capacities. The capacities of an individual agent refer to sensor, motor and cognitive capabilities (i.e., capacities to reason and communicate). Wickens (1992) provides a model of human information processes that can serve to investigate the limitations of these capacities. In this model, a (human) agent carries out visual, auditory and kinesthetic sensory processing to handle stimuli. A short-term sensory store for each modality represents the details of the stimulus for a short period of time after it has occurred physically. For visual information, this period is less then a second, for the other two modalities two to eight seconds. No conscious attention is required for short term sensory store.

The next step is encoding the stimulus permanently in long-term memory as a single perceptual category after it has been perceived or recognized (i.e., has been linked to previously learned perceptual categories already stored in long-term memory). Different levels of categorization can be distinguished. Detection is a task at the least complex level.

Recognition, identification and categorization are more complex tasks. When more categorical dimensions are involved, pattern recognition takes place.

After the stimulus is encoded, the agent has to decide what action should follow. One possibility is to select a response. Deciding what to do can be made after some considerations but also immediately. Another possibility is to delay an action by storing the information temporarily into the working memory. To retain this information in the working memory it should be actively rehearsed. A second option is to learn it by storing it in long term memory.

After a response is selected it will be executed. The response uses a particular plan to perform the action. The execution of the plan is monitored in a closed-loop feedback structure.

When the resources are still insufficient to carry out a task, one option is left: forming a team of multiple agents. Within this team, agents have a position (e.g., a position in a hierarchy) which gives them responsibility, and they must act within certain constraints. These constraints can be divided in permissions (formal agreements within an organization on the performance of particular tasks), norms (ethical considerations in performing a task), and preferences (about how to carry out a (combination of) particular tasks) (Wærn & Gala, 1993).

Stress. Information processing capacities are influenced by stress factors, such as noise, anxiety and incentive, fatigue and sleep loss etc. Effects of stress may be attentional narrowing, working memory loss, shifts in the relation of speed versus risk, and decision making performance decreases (Wickens, 1992).

Knowledge. (Human) agents store three types of information in their long-term memory: skills, rules, and knowledge (Rasmussen, 1983). Skills refer to automated and highly integrated patterns of behaviour. Rules are condition-action relations to handle previously experienced situations. Knowledge refers to models one has of (a part of) the world. By using this knowledge problems not encountered before can be solved. A number of authors distinguish two types of knowledge: *domain knowledge* (i.e., facts within a particular domain) and *problem solving knowledge* (knowledge about how to make inferences given the problem description and how to combine these inferences to solve the problem) (e.g., Clancey, 1985; Wielinga & Breuker, 1986; Van Heijst et al., 1994).

Learning. Skills, rules and knowledge are acquired through the process of learning. Knowledge is either passed through by others or is acquired by experience. Becoming skilful or an expert in a certain domain is time-consuming. Therefore, skills and expertise are distributed over the members of a team rather than similar for each member. Further, knowledge, once acquired, is not static but changes through task execution. This process needs feedback and knowledge of results.

2.5 Agents can form a team

As has been pointed out above, the knowledge and capacities of an agent are limited. For certain tasks, these limitations prevent the agent to perform the job. One of the possibilities to extend the knowledge and capacities by carrying out the job with more than one agent. Van de Velde & Perram (1996) define multi-agent systems as "[...] distributed systems that are designed as a collection of interacting autonomous agents, each having their own capacities and goals that are related to a common environment." In the definition of *team* given by Dyer (1984), cited in the introduction, three factors are important for distinguishing teams from other multi-agent systems: cooperation (to realize a shared mission), interdependency (the mission cannot be fulfilled without the other members), and heterogeneity (the members differ with respect to expertise, roles and responsibility). Three typical characteristics of teams can be added. First, the interdependency is often caused by the need for real-time problem solving; a single agent with limited knowledge and capacities cannot just take more time to finish his or her job, because there is a deadline. Moreover, when real-time problem-solving should be carried out continuously, shifts are necessary to refresh a team. Second, teams are limited in size. Otherwise, the overhead in communication and coordination decreases team performance. Third, teams are relatively permanent, and have the opportunity to train *communication* and *coordination*. Communication and coordination are tasks that are specific for teams (an not for single agents). Many authors stress the importance of these two tasks (e.g., Stout & Salas, 1993; Rouse et al., 1992; Adams, 1995). Communication and coordination are discussed in more detail next.

Communication. Information needed to perform a task is distributed among team members by means of communication. Communication is not always a question and answer sequence. Typical for well-performing teams is the anticipation of information needs, so as to present information before it is asked for (Rouse et al, 1992). Serfaty et al. (1993) suggest to use this feature to measure team performance and propose an anticipation ratio: the relation between provided info and asked info.

According to Orasanu (1993), communication is very task-directed and involves plans, strategies, intentions, possibilities, explanations, warnings, and predictions. Information about task-related needs, positions, roles, needs, responsibilities, and expectations can be planned in advance. For successful teams this takes place during low work pressure (Orasanu & Salas, 1992; Stout & Salas, 1993).

Communication can be categorized in direct and mediated communication. Direct communication can have different modalities (speech, touch and vision). Chapanis et al. (1977) investigated the effectiveness of direct speech and vision on team problem solving (i.e., two person teams). Teams that were able to speak with each other solved their problems twice as fast as teams that communicated without speech but by teletype writing. The results should be handled with caution, however, since the tasks (a design task and a search task) may not be representative for all tasks. In addition, the teams consisted of two members only,

who were not used to each other. Moreover, the team tasks were not carried out under time pressure.

Fussell and Benimoff (1995) distinguish three direct communication channels: linguistic (verbal), paralinguistic (intonations and pauses), and non-linguistic (non-verbal, such as gestures, postures) communication. They regard communication as a coordinated activity in which all three channels can take part. Some coordination activities are turn taking (such as by a falling or rising intonation characteristic of the end of a sentence), and back-channel responses (such as "uh-huh").

Much information is not communicated directly but is mediated. This information can be textual or pictorial. Team members can type in a message and send it to each other. For this way of communication, the message should be clear enough to be understood, without any further explanation. Communication with text and pictures can also be used in a more interactive way, within a shared work space. One can make conceptual graphs of a problem, use conference screens or general plots to aid communication, etc. Whittaker, Geelhoed and Robinson (1993) and also Tang (1991) found that such shared work spaces are especially useful when the task has a substantial graphical component. The deictic element (i.e., pointing to something instead of describing it) is generally an important element of communication (see e.g. Cremers, 1996) and therefore may need to be supported in mediated communication.

We distinguish four different categories of communication:

- *Data communication.* This type of communication is highly task related and involves information needed to complete the task. People may explicitly ask for data information, or give this information voluntary.
- *Task communication.* During a task, members of a team may inform each other about the process of task completion. Team members log their activities by telling each other what they are doing on a particular moment. Also team members correct each others utterances and express their workload in demanding situations. Furthermore, evaluation of the task performance takes place and team members coordinate their activities by agreeing upon an new division of tasks. Sometimes a team member takes over the other team members' task without deliberation.
- *Domain knowledge communication.* Team members speak about learned rules and strategies. Also team members evaluate former actions and formulate new strategies to improve their performance. This type of communication is typical for intra-team feedback.
- *Meta-communication.* Meta-communication is communication about the management of communication (Clarke, 1996), or in other words, communication for coordinating communication. An example is asking to restrict communication to the necessary ingredients, to necessary communication lines, or to status changes only.

In addition to the above described categories *communication control* take place as well. This communication consists of utterances which indicated if a message was received and understand. Examples of these utterances are "okay" or "roger".

Communication can be supported technically with electronic conference lines and point-to-point connections.

Coordination. Our definition of coordination is "a task in which other tasks, including communication, are organized in terms of work allocation over time, space, and agents".

Adams (1995) provides a framework for closed-loop real-time team work processes in which coordination has a key role. He distinguishes external and internal coordination. External coordination handles inputs of external agents (supervisory agents or cooperative agents). Internal coordination deals with controlling or guiding real-time tasks.

Cooperation. The term cooperation is also associated with teams. Clarke (1996) uses the following definition of cooperation: "acting together in a coordinated way [...] in the pursuit of shared goals [...]" (p.59). Clarke (1996) distinguishes three different levels of outcome: *(i)* efficiency, where cooperation minimizes the effort required to achieve the goal (this refers to the coordination aspect, such as synchronization when moving a piano); *(ii)* possibility, where the partners can achieve goals not possible for one person to achieve (e.g., when moving a piano); and *(iii)* synergy, where the cooperating partners can together achieve a different order of result from that achievable separately (such as when playing quatre-mains).

The structure of teams. Team members have an interrelationship. They differ in expertise, roles, and responsibilities. The performance of a team depends on how the team is structured. Hierarchically organized teams perform worse than other teams under heavy workload; under low and medium workload, teams with overlapping tasks perform better (Urban, Bowers, Monday & Morgan, 1995).

Team training. Within a team, learning is needed to get used to each others way and to improve coordination and communication tasks. One way is to let the members of a team perform the tasks of their colleagues. Cross training does not increase team performance perse. It does increase the knowledge of each others' information needs (Schraagen & Rasker, 1996; see also Schaafstal & Bots, 1997). This, however, pays only in hectic situations where seconds can make a whole difference.

2.6 Shared mental model set

Considering the overview of literature presented above, the concept of Shared Mental Model can be worked out in more detail. We will propose the following six submodels:

- Shared Situation Model. This encompasses a description of the current situation, possibly extended with history information;
- Shared Organizational Resources Model. Here an overview of the organizational resources is modelled, such as manpower (the agents with known knowledge and capacities), machines, tools, the availability and deployment of assets, etc.;

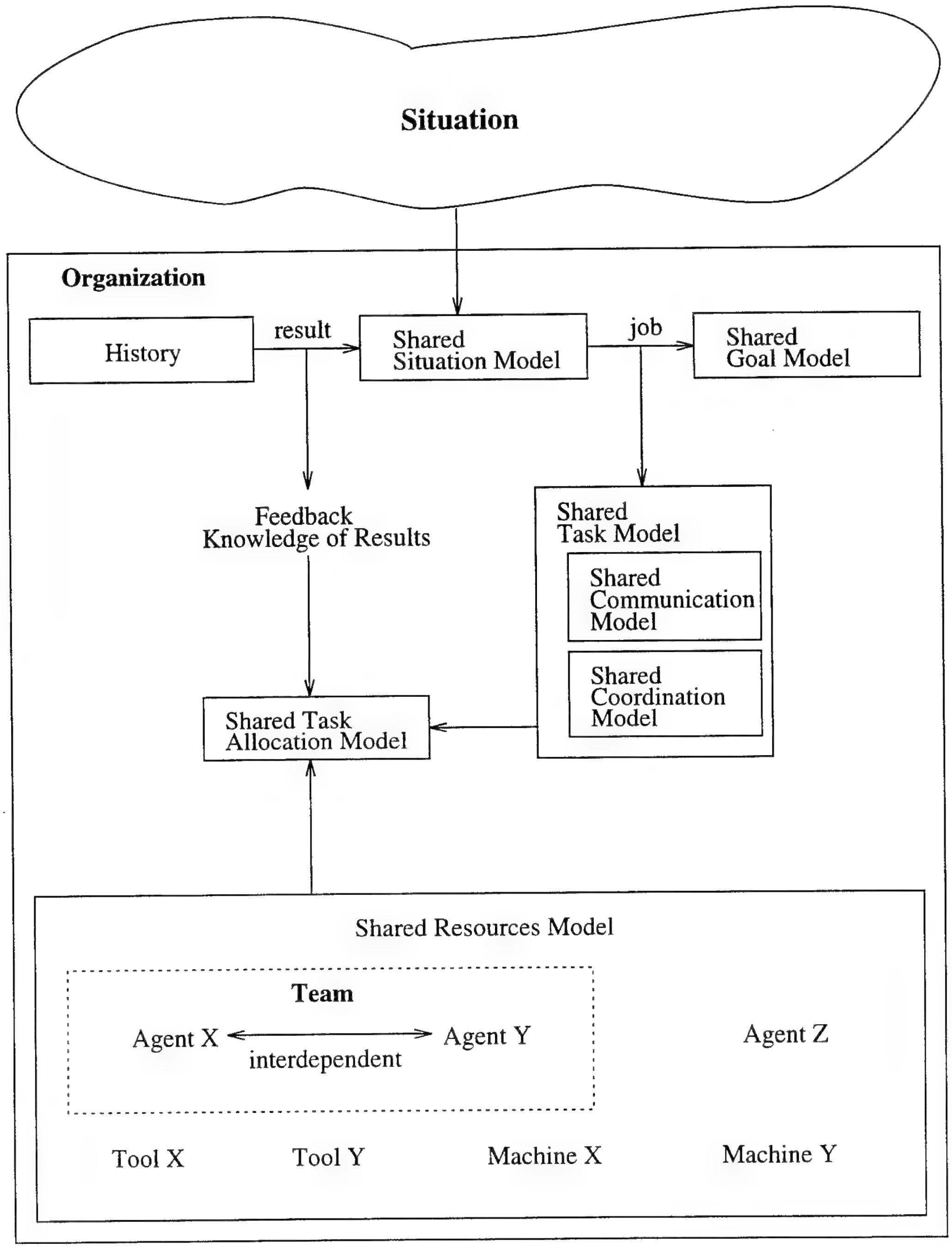

Fig. 1 The shared mental model set from the perspective of the organization.

- Shared Goal Model. The Goal Model states a description of the situation the organization is aiming for at a certain point in time; (e.g., safe and timely arrival at point p and time t.)
- Shared Task Model, expressing the tasks to carry out to realize the goal in time;
- Shared Communication Model, which is a submodel of the Task Model; in this model, the conventions of communication are defined;
- Shared Coordination Model, also a submodel of the Task Model;

- Shared Task Allocation Model, describing the links between the tasks and the organizational resources; important for team functioning is to know each other's position, function and expertise.

Figure 1 presents these models graphically from the perspective of the organization. This figure shows an organization that has to deal with the situation it is part of. The situation is described in the Shared Situation Model. The current situation has a History. Previous actions of the organization have resulted in the current situation, and the result is described in terms of Feedback and Knowledge of Results. The organization has a common goal, defined in the Shared Goal Model. The discrepancy between the Goal and the current situation defines the job the organization has to carry out. This job is accomplished by performing tasks, described in the Shared Task Model.

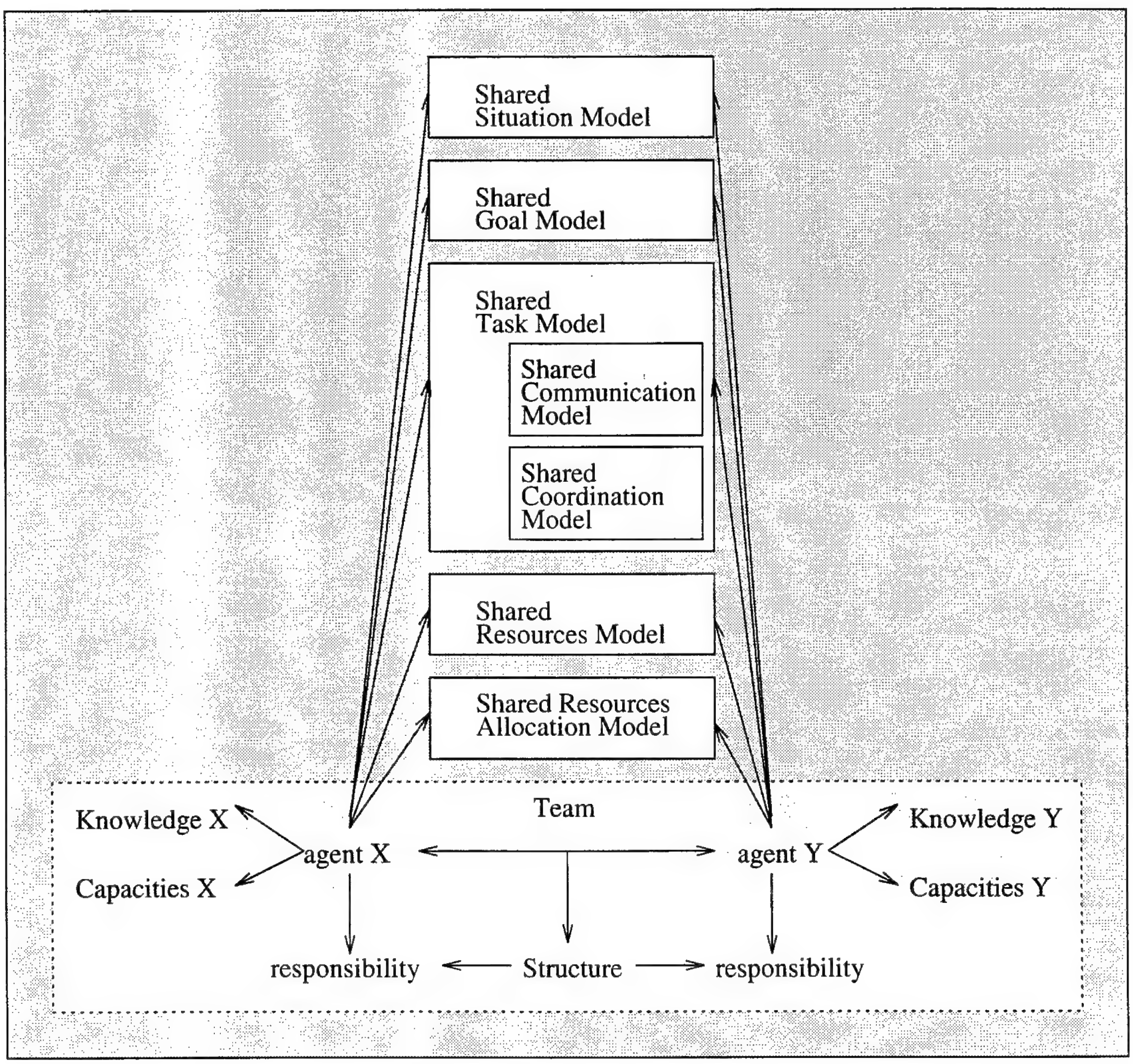

Fig. 2 The Shared Mental Model set from the perspective of the agent.

Two sub-models of the Shared Task Model are the Shared Communication Model and the Shared Coordination Model. The organization has resources available to realize its goal. These are defined in the Shared Resources Model. This model describes the agents and their possible interdependence, and the tools and machines available. When agents are interdependent, they form a team. Based on previous results of allocating the resources, the current resources of the organization are allocated to the tasks defined in the Shared Task Model.

From the perspective of an agent, the model is presented in Figure 2. An individual agent has sensory, motor and cognitive capacities, and possesses domain knowledge and problem-solving knowledge. Both knowledge and capacities are limited. For realizing a common goal they cannot reach by themselves agents can combine knowledge and capacities by forming a team. For working together, agents need to communicate and to coordinate their actions. To enhance communication and coordination, they need shared mental models of their situation, their goal, the tasks necessary to realize the goal, the resources available (including the knowledge and capacities of their fellow agents), and how the resources are allocated to the tasks needed to be carried out. The relation between the agents of a team is structured (e.g., a hierarchical relation between agents), and because of this interrelation, they may have responsibilities.

2.7 Conclusions

In summary, we have described a framework of team knowledge and information consisting of various elements: the situation, the organisation, its tasks, and the allocation of tasks to agents. These elements guide our research on communication and coordination further in the next chapters.

Based on the models proposed, team performance may be enhanced by compensating for the limitations of the individual agents as follows:

- individual agents need to learn individual skills, rules and knowledge (both problem solving knowledge and domain knowledge). To shorten learning time, the elements of expertise may be optimally distributed over the members of a team;
- team members should particularly learn how to communicate and coordinate;
- team members can help reduce stress by noise reduction, anxiety reduction, and by increasing the incentive;
- team members may extend the working memory of others;
- team members can provide the skills, rules and knowledge (both problem solving knowledge and domain knowledge) in their long-term memory to others;
- team members may watch each other on tunnel vision, biases, and errors (mistakes, lapses and mode errors, and slips; see for example Wickens, 1992); team members can also distribute problem solving subtasks; this is proposed by the work of Cohen (1993). Cohen states that not all problem solving tasks are based on recognition; sometimes, meta-

cognition takes place, meaning that the problem-solving process is analysed in more detail. This process can be done by more than one person: one agent can take on the role of the devil's advocate and can generate alternative explanations that contradict the outcome of pattern recognition performed by another agent (e.g., in uncommon situations, when the stakes of an error are high, when some time is left over, etc.).

This list is too large to be captured in one study. As has been mentioned in § 1.3, we focus our research on the necessity for working with more than one agent, the conditions of communication and coordination, and the distribution of knowledge within a team.

3 FIRE-FIGHTING PARADIGM

In order to investigate the role of communication and coordination in team decision making we will simulate situations that a fire-fighting organization has to handle. By varying the way in which communication can take place within this organization, insight will be gained in how these factors contribute to team performance. First, we will explain the situation. Next, we describe the organization. Then, we analyse the tasks to handle the situation in detail. After that, we describe different types of teams that should carry out the tasks.

3.1 Situation

The situations take place in a city. This city consists of 76 buildings that are located in one of four sectors. At certain points in time, a series of fires threatens the city. These fires take place during a time frame of 12 time periods. Table I shows these time periods.

Table I A scenario of 12 time periods representing the situation that has to be dealt with.

Period	1	2	3	4	5	6	7	8	9	10	11	12
Building (76)	house	school		house	house			complex			hospital	
Sector (4)	south	north		east	east			east			west	
Possible casualties	2	100		2	2			10			1000	
Units needed	1	3		1	1			2			5	

In the example scenario, first a house gets on fire, next a school, again a house, a complex, and finally a hospital. When a building burns down, a number of lives are lost. A house has two potential victims, a complex 10, a school 100, a factory (not shown in the example scenario) 500, and finally, a hospital 1000. To save the lives, fire-fighting units are needed. For a house, 1 unit suffices, a apartment building needs 2 units, a school 3, a factory 4, and a hospital 5.

3.2 Organization

In order to handle this situation, a fire-fighting organization has been set up. The organization has formulated a goal: to rescue as many lives as possible. The resources of the organization are restricted: only 6 fire-fighting units are available. In a dispatch centre, information about the fires is collected and the fire-fighting units are allocated.

The scenario shows that the most important building to save is the hospital. This fire can be prevented when sufficient units are located at the hospital at the onset of the fire. Unfortunately, the fire-fighting units need one time period for transportation between the fire-fighting station and a particular building. The scenario also shows that not enough units are available after having assigned the units to the fires started earlier. Withdrawing a unit takes one time period as well. So, when the hospital (or in other scenarios, a factory) gets on fire, the fire fighters will always be too late. However, the organization possesses pattern knowledge of series of fires that can be used to predict the location and the type of a large building that will get on fire. When three small buildings in one sector will get on fire (in the example scenario, two houses and a appartment building in sector east), a large building will get on fire in the opposite sector, three time periods later (in the scenario, a hospital in sector west). This knowledge can be used to (re)allocate the resources in time.

3.3 Tasks

We analyse the fire-fighting task in detail. First, we decompose fire fighting into subtasks, and allocate the subtasks to agents. Next, we analyse the types of information and knowledge used in the subtasks. Based on this, we will perform a time-line analysis for fire fighting in an experimental environment that will be introduced in the next chapter. The task analysis and the time-line analysis yields a normative description of the experimental task. This will be used to define the measurements for team performance.

3.3.1 Task analysis

Fire-fighting can be divided in four sub-tasks: situation awareness, threat assessment, decision making and execution. This decomposition is based on the generic functions suggested in van Delft & Schuffel (1995). These sub-tasks are further decomposed into a task hierarchy presented in Figure 3. The type of information and knowledge that is used in the subtasks are depicted in Figure 4. We will explain each sub-task in detail.

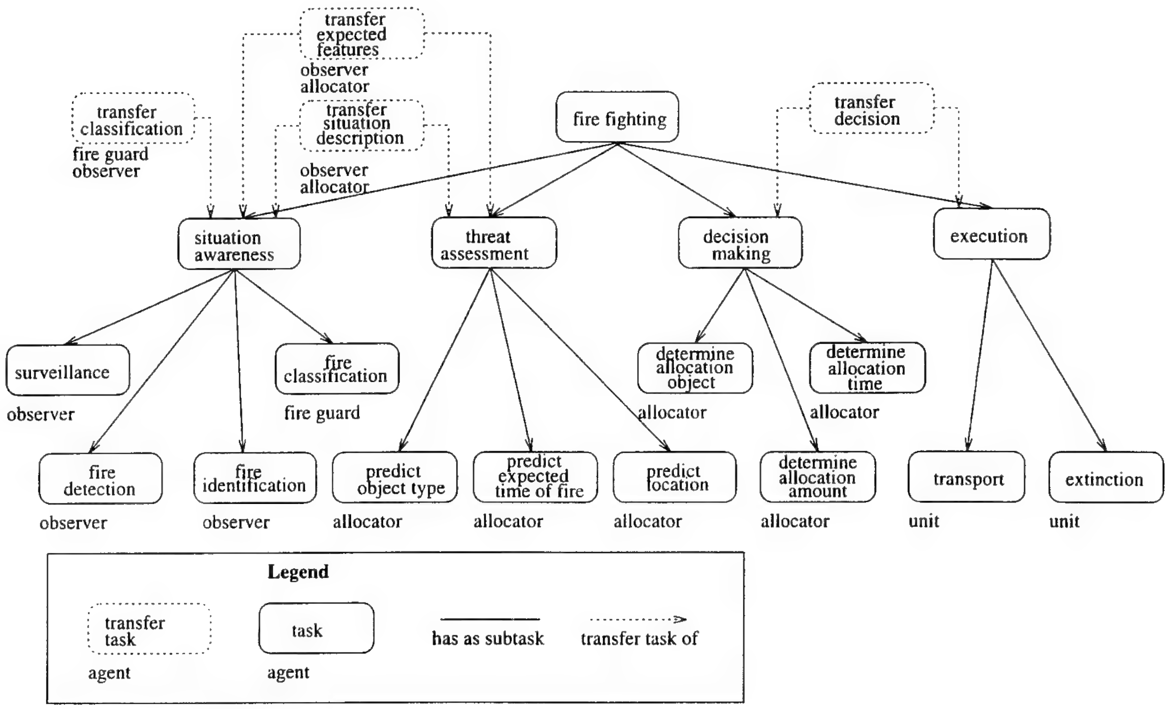

Fig. 3 The task-hierarchy of fire fighting.

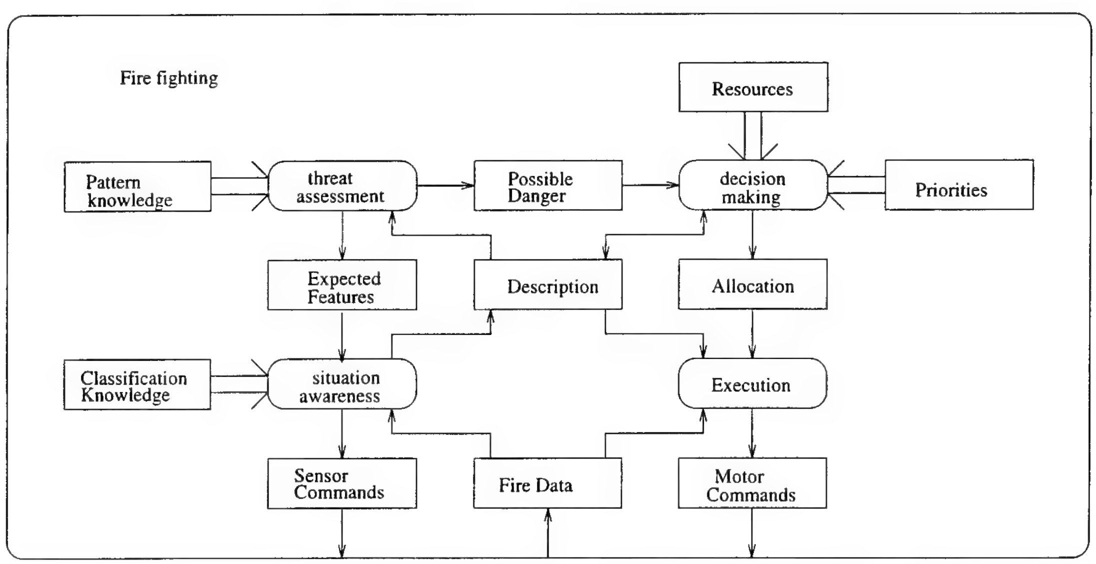

Fig. 4 Information and knowledge in the fire-fighting task. The rounded boxes denote (sub-)tasks; the square boxes information; the arrows data dependencies; and the double arrows knowledge dependencies.

Situation awareness is monitoring the outside world on fires. Situation awareness is decomposed further in *surveillance* (searching for potential danger), *fire detection* (perceiving a fire), *fire identification* (identifying the location and the type of fire, that is, whether it is a

house, a hospital, etc.) and *fire classification* (i.e., categorizing the fire-state: whether it is on fire, burnt-down, or under control). Surveillance uses information of expected features (the location, moment, and type of object of an expected fire) to guide the search in the outside world. Fire detection uses information in the outside world to detect an object on fire. Fire identification describes the object on fire (in terms of location and type of object) based on knowledge of coordinates and object types. Finally, fire classification uses knowledge about possible fire states to classify the severity of the fire.

The second task, *threat assessment,* is concerned with the assessment of the overall situation, that is, the relation between the fires in terms of time and place. This is used to predict and anticipate future fires, based on recognizing patterns of the buildings on fire, which is important for decision making. The task is decomposed in *predict expected time of fire, predict object type* and *predict location.* The task uses information of the overall situation (i.e., the fires, the order of fires, and the location of fires) to generate features of an expected fire (the expected location and the expected type of object). These features are used in the situation awareness task for guiding surveillance. Situation assessment also generates a description of a threat (i.e., a fire), in terms of expected time, location, and object. This threat description is used in the decision making task to anticipate deployment. The threat assessment task uses knowledge about patterns of fires for predicting new fires.

The third task, *decision making,* results in a decision about the deployment of units. The task consists of *determine allocation object, determine allocation amount,* and *determine allocation moment.* The "determine allocation object" task determines to which object a unit should be allocated, or from which object a unit is withdrawn. This task uses information about the situation of the objects, and knowledge about priorities (i.e., the importance of objects in terms of number of victims). The "determine allocation amount" task is concerned with how many units to allocate (or withdraw). This task is carried out with information about the current amount of units allocated to the objects, and the current state of the objects. The task also uses knowledge about the deployment duration of units. The "determine allocation moment" task determines at what moment a unit should be allocated or withdrawn. The task uses information about the possible threat (especially the expected time), and knowledge of deployment duration.

The fourth and final task, *execution,* is divided in transport and extinction. Execution is expected to have impact on the outside world. That is to say, there is no deterministic relation between the execution of a cognitive task and the effect of it on the outside world, only a probabilistic one (the intended effect may be reached). The impact is mediated by a motor agent which receives its orders from the execution task. The execution task generates the orders using the decision taken, the situation model and the fire data.

Learning fire-fighting

As with all tasks, fire fighting should be evaluated in order to optimize the task. Here we present a tentative model of how this evaluation takes place. The evaluation is based on feedback of how the task is performed and on quality norms. Task optimization will take place when performance and quality norms are not in agreement. The optimization is carried out by adapting the knowledge about the domain (such as about existing objects, priorities etc.), knowledge about how to carry out the tasks (i.e., the order, start and finish of tasks), and knowledge about how to communicate. The knowledge does not change continuously during task execution, only after having received feedback. Changing the knowledge also depends on the available time to reflect on the performance.

Background knowledge is also involved in task execution. Missing knowledge about the domain, the task, and communication is compensated by prior knowledge that one has about the task, or a similar task. Figure 5 shows the tasks and the information dependencies graphically.

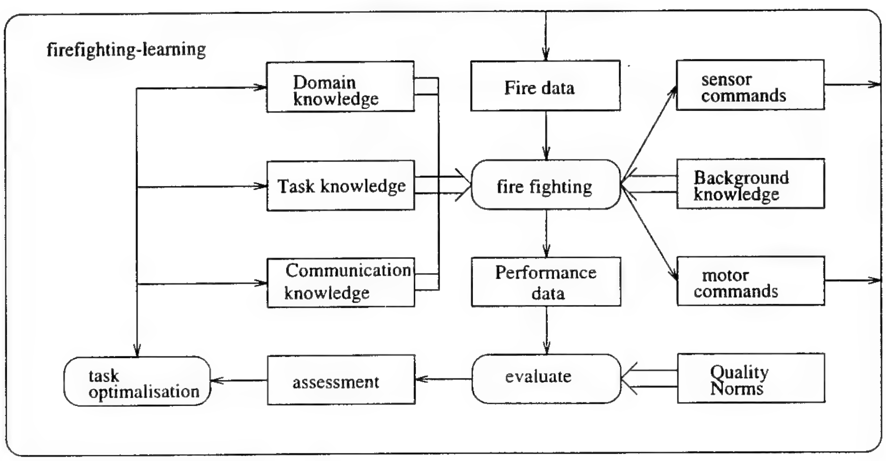

Fig. 5 Learning fire-fighting.

3.3.2 Task allocation

In the experimental environment, the tasks are allocated to different types of *teams* consisting of different types of *agents: fire guards, fire-fighting units,* the *observer* and the *allocator*. The fire guards can provide information about how many units are needed: the fire classification. This information, however, should explicitly be asked for by the observer. The observer takes account of surveillance, fire detection, fire identification, and is involved, together with the fire guard, in transferring fire classification information to the allocator. The observer is involved, together with the allocator, in transferring the description of the situation. The allocator carries out the threat assessment, predicts object type, predicts expected time of fire, and predicts location tasks. The allocator transfers the decision to the

units. The units carry out transport and extinguish the fires. The allocation of the tasks and the transfer tasks are shown in Figure 4 as well. In the experimental environment, the fire guard and the fire units are software agents.

In the next section, the task analysis described above is extended with a normative description of the task by means of a time-line analysis.

3.3.3 Time-line analysis

By performing time-line analysis, we will establish action charts for the fire-fighting tasks. A time-line analysis of the tasks depends on how the tasks and the knowledge are distributed among the agents and in space. Figures 6–9 present the action charts for four different conditions. In the first condition, fire fighting is carried out by a single agent. In the second condition, a fire-fighting team, consisting of an observer and an allocator, perform fire fighting in a face-to-face situation. In the third condition, the two members of the fire-fighting team are physically separated, and the team does not share knowledge of how to assess the threat; only the allocator possesses this knowledge. Communication is restricted to a minimum: only the information to perform the tasks, such as the buildings that are on fire and in threat, are exchanged. In the fourth condition, the situation differs at one point with the previous condition: both the observer and the allocator have threat assessment knowledge available.

The action charts only show the time periods 7, 8 and 9. In these time periods, task performance is most critical and therefore the focus of the present investigation. Because the large buildings will get on fire at a fixed time (in time period 10), the action charts need only to describe some critical time periods in advance. The first six time periods are not critical (i.e., sufficient time is available to carry out the tasks). At the beginning of time period 7, the last piece of information becomes available for recognizing a pattern that is used for searching and finding the large building under threat. Assessing the threat and finding the threatened building too late delays (re)allocation of the fire units, which has serious consequences for being in time to rescue the large building.

Condition 1 : individuals

In the condition presented in Figure 6, the single agent starts, at the beginning of time period 7, with a situation awareness task (denoted by SA). He or she detects a building on fire and identifies the object type. Knowing what the previous buildings were, he recognizes a pattern (marked by TA), and is now able to predict the object type and the location of the fire that is expected to start in time period 10. Next, he starts to determine how many fire units he needs to send to the fire, and if not enough are available in the fire station, from which objects they need to be withdrawn (indicated by DM). Also, the fire-units have to be notified (referred by C, meaning communication). Now, a surveillance task can start in which he will search for the threatened building of a certain type and at a certain sector (SA). After the threatened

building has been found, the building is added to a plot board (C). Finally, he allocates the available fire units to the threatened building (DM) and has to inform the fire units (C).

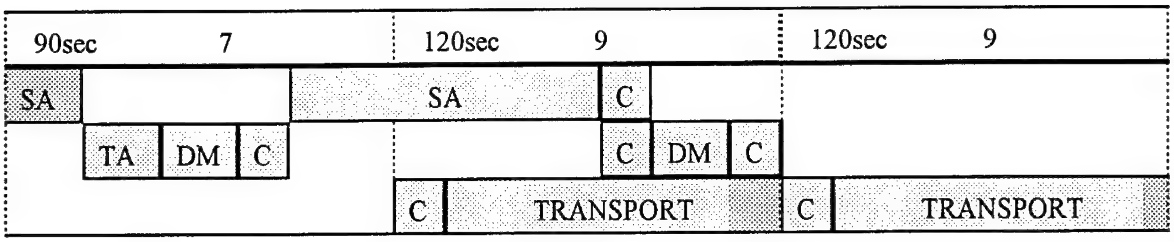

Fig. 6 Individual condition.

The agent has to work with two important deadlines. Since the fire-fighting units only receive messages at the beginning of a time period, and the remaining time period is needed for transportation, it is essential that decisions about withdrawing units (in time period 7) and about allocating units (in time period 8) are communicated in time, that is, before the start of a new period. Otherwise, transport is delayed with a full time period. The most critical task is the surveillance task (the second SA task in the figure). When the building under threat is not found in time, the fire-fighting units will arrive too late at the building, causing many casualties. Therefore, it is important to start this task as early as possible. In Figure 6, the length of the second SA task represents the *available* time for searching; how much time the task takes depends on the chance of finding the threatened building. The duration of the other tasks are always the same.

Condition 2: unrestricted communication

Figure 6 clearly shows that the tasks are carried out sequentially. One way to start earlier with the search for the threatened building is to carry out tasks in parallel. To do this, a second agent is needed. Figure 7 shows this condition.

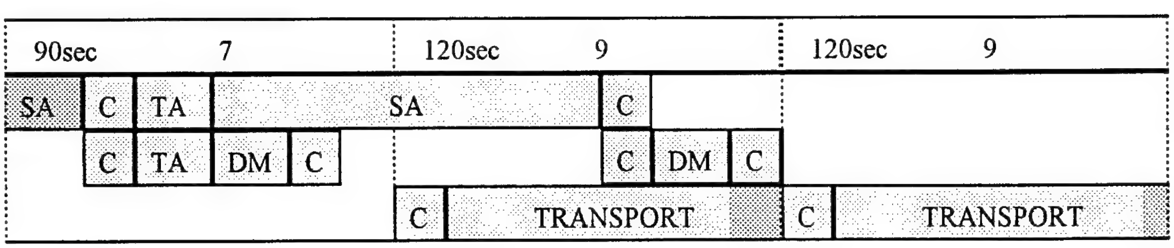

Fig. 7 Team with unrestricted communication.

The observer starts with situation awareness. The last piece of the pattern is communicated to the allocator, and the observer can continue directly with threat assessment, and with

searching for the threatened building, once the building type and location is determined. In parallel, the allocator has assessed the threat and withdraws fire-fighting units. Compared to the previous condition, there is some overhead for necessary communication, but the second SA task can start earlier, and more time is left for finding the threatened building.

Condition 3: restricted communication without shared knowledge

Figure 8 shows a condition in which team members can communicate and coordinate in a restricted way. Only necessary ingredients are communicated. As one can see, an important dependency arises: the observer has to wait at least for the allocator having assessed the threat (the allocator may also follow the strategy first to decide to withdraw units, and having notified this to the fire units before communicating the threatened building type and sector to the observer; this in order to send the message to the units before the deadline is reached).

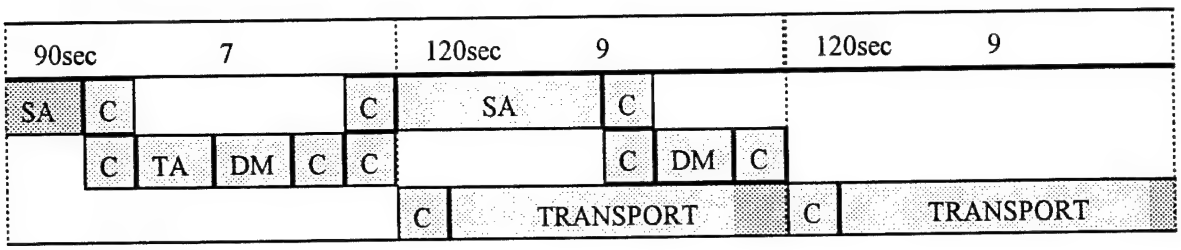

Fig. 8 Team with restricted communication *without* shared knowledge.

Condition 4: restricted communication with shared knowledge

Figure 9 shows a condition in which the dependency of condition 3 is minimized by providing the observer with pattern knowledge; threat assessment can now be carried out by both team members.

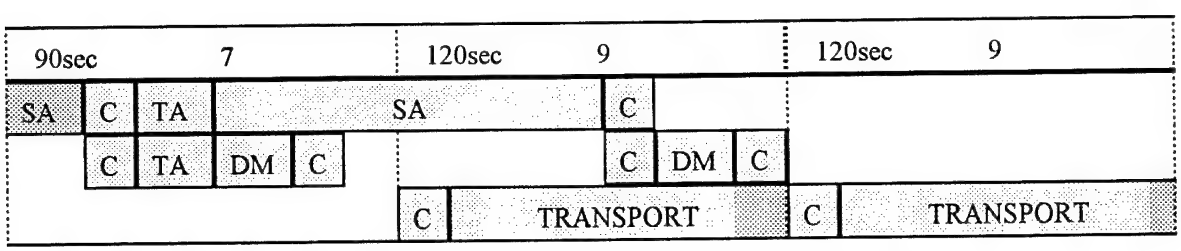

Fig. 9 Team with restricted communication *with* shared knowledge.

3.4 Hypotheses

We have now all the ingredients at our disposal to translate our three research questions stated in § 1.3 into testable hypotheses. The framework presented in chapter 2 tells us that when an agent is not able to perform a job alone, he can form a team; the task analysis in the previous section predicts that for the fire-fighting task, an individual indeed performs less well than a team. Further, our task analysis does not predict differences between unrestricted and restricted communication. However, the framework describes that teams communicate not only data, but also domain knowledge and task information. Also, the framework indicates that members rely on knowledge to carry out their tasks; the task analysis predicts that shared knowledge decreases interdependency among team members. This all leads us to formulate the following three hypotheses:

1 Individuals can not perform the task well because they are not able to perform crucial task elements in parallel.

2 Communication restricted to data exchange leads to a decrease in team performance, since other types of communication contribute to team performance as well.

3 Restricting shared knowledge to one team member leads to interdepedency increase and therefore to team performance decrease.

4 METHOD

This section gives a description of the method used. In total, the experiment consisted of the four conditions described in § 3.3.

4.1 Subjects

77 students of the University of Utrecht participated in the experiment. Their mean age was 23 years (σ=3). 11 subjects participated in the individual condition (7 male and 5 female) and 66 subjects participated in the teams condition (34 male and 32 female). Each team consisted of 2 subjects. 22 subjects participated in the unrestricted communication condition. Each team consisted of two subjects of the same sex (6 male teams and 5 female teams). 22 subjects participated in the restricted communication condition *without* shared knowledge and 22 subjects participated in the restricted communication condition *with* shared knowledge. For both conditions with restricted communication, male and female were divided as follows: 6 teams with subjects of the same sex (3 male and 3 female) and 5 mixed teams (2 teams with a male allocator and 3 teams with a female allocator). The subjects were paid Dfl. 60,= and were informed that they had a chance of receiving a bonus of Dfl. 40,=. This bonus was given to the best-performing individual and to each subject of the best-performing team for each condition.

4.2 Task

Subjects were required to imagine that they were operators of a dispatch centre of a fire-fighting organisation of a city, as outlined in § 3.3.1. The mission of the subjects was to fight fires in order to keep the number of casualties as low as possible. A computer simulation, especially developed for this type of experimental research (see Schraagen, 1995), represented the functions of the dispatch centre. The computer simulation was designed to support the tasks of an observer and an allocator. A separate interface was available for each of them. For the detection task the subject was presented with a map of the imaginary city in which the buildings were shown as icons. The subjects were informed about the state of the buildings by graphical means (red for fire, black for burn down, and green for extinguished). The four sectors of the city were represented by boundaries on the map. Every building in the city had its own identifier annotated, for example house_A(I) (the roman character informed the subject about the sector where the building was located). When the status of a building changed, the observer could inform the allocator about this by first clicking on the icon. This provided him or her with information about the fire (numbers of units needed, possible danger). Next, to send this information to the allocator, a standardised e-mail function was available.

The allocator could assign the six fire units by first loading the message of the observer into a plot board, by clicking on a button. Next, he or she had to indicate to which building on the plot board a fire-fighting unit has to be send (or withdrawn). The number of fire units which had to be allocated, depending on the type of building and the progress of extinction, was represented on the plot board as well. The information about the progress of extinction, and subsequently the number of fire units needed, were sent by the observer by standardized e-mail. In turn, the allocator could inform the observer by standardized e-mail about the number of fire-units which were allocated to a building. The standardised e-mail could also be used for asking questions about the number of fire-units needed or the number of fire-units allocated. Communication which took place via the e-mail was purely task related. Therefore, the standardised e-mail should be regarded as data communication only.

Recall from chapter 3 that to keep the number of casualties as low as possible, fires should be detected as quickly as possible and sufficient fire units should be allocated in time. Recall also that beside some small buildings like houses or a school, each scenario contained at least one burning factory or one burning hospital. Minimising the number of casualties was highly dependent on how well subjects succeeded in extinguishing the fires of these large buildings. Recognising a certain pattern of fires in small buildings made it possible to predict a fire in a large building. Anticipation of these fires (on basis of the pattern) was necessary for achieving a low number of casualties.

A pattern was made up of three small buildings (houses and apartments) which, one at a time, had been on fire in the same sector. The type of buildings and the sector where the pattern was presented, predicted a possible future fire in a large building elsewhere. The principle

was that a pattern of three small buildings (houses or apartment buildings) in one sector predicted a fire in a large building located in the diagonally opposite sector. In order to find this threatened building, subjects had to search for a special warning. Searching was done by scanning the map, by means of clicking each building with the computer-mouse. When the warning was found the subjects had information about the exact period that the threatened building would be on fire. To save this building, fire units had to be reallocated from small buildings toward the large building. The exact type of large building (factory or hospital) could be predicted by the final building of the pattern (a house meant that a factory would go on fire, an apartment-building meant that a hospital would go on fire).

In some scenarios the e-mail was distorted (only during the experimental task, not during training). This was done by adding a different label to a building (for example, complex_F(IV) instead of complex_S(I)). The distortion of the e-mail was fixed as follows. First, only the mail transferred from the detection screen to the allocation screen was distorted. Second, only the mail concerning a building in the middle of a pattern of three small buildings was distorted. Third, the distortion only influenced information concerning the identification and the sector, thus information concerning the type of building remained the same. Consequently, it was no longer possible to predict an upcoming fire on the basis of the information received by the e-mail in the allocation task.

Besides some scenarios with distorted e-mail, there were also "non-routine" scenarios developed (only during the experimental task, not during training). In these scenarios the newly learned knowledge about patterns was not applicable. This was due to the fact that the location of the fire was different than would be expected on the basis of the pattern (instead of occurring in the diagonally opposite sector, the fire would occur in one of the three remaining sectors). Nevertheless, the prediction with regard to the type of building (factory or a hospital) remained intact.

An elaborate description of the experimental task can be found in Schraagen and Koster (1996).

4.3 Procedure

The experiment was divided into four parts: three training sessions and the actual experiment. The first training session was intended to teach subjects to use the interface of the simulation of the fire-fighting station. Therefore subjects had to read a written instruction. This instruction contained global information about the mission of the task and specific information how to use the computer-mouse for clicking different buttons on the screen. Also this part of the written instruction contained some exercises. These exercises had to be performed with a stationary screen (at that instance a scenario was not running). In that way all aspects of the screen and the buttons used were explained one step at the time. Compared with the subjects in the three teams conditions, the training was different for the subjects in the individual

condition. Subjects in the individual condition had to control both screens simultaneously. That is, they had to perform the detection task as well as the allocation task. To control both screens subjects had at their disposal a specially designed computer-mouse whose cursor could be moved from one screen to the other. In contrast with the individuals, each subject in the three team conditions was assigned to either the detection task (observer) or the allocation task (allocator).

The second training-session was intended to teach the subjects how to perform the task. During the second training-session the subjects were presented with 16 scenarios. They started with moderately difficult scenarios and ended with difficult scenarios. A scenario was more difficult as the number of buildings set on fire increased. Furthermore the succession of fires took place in a shorter time notice. As a result the subjects had to make decisions under high time pressure during the difficult scenarios. Also the subjects had to prioritise the buildings as the number of fire-units was limited. The subjects in the three teams conditions were trained separately and were not allowed to talk to each other. Their teammates were played by an automated software agent. These agents (one for the detection task and one for the allocation task) were modelled in such a manner that their behaviour was similar to a human performer. In this way it was possible to train each subject under controlled conditions, since subjects did not work together and they were not susceptible to each others' behaviour and possible mistakes. Moreover, each software agent always behaved in the same matter.

After finishing the second training-session, subjects were presented with another written instruction. This instruction was intended to teach the subjects how to recognise patterns. The information concerning pattern recognition was different for the restricted communication condition *without* shared knowledge in comparison with the teams of the other conditions. In the condition without shared knowledge only the allocator was informed about patterns, while in the other conditions both team members were informed so that the observer had the same task knowledge as the allocator. Subjects trained in pattern recognition had a list with patterns and threatened buildings at their disposal, which they could use during the experimental task. After reading the instruction the subjects were trained in another 16 scenarios. These scenarios were developed in order to train the subjects in applying the newly learned knowledge about patterns. The subjects in the teams condition were trained with the aid of the automated software agents which were also used during the second training-session. The experimental task was preceded by a brief written instruction. This instruction informed subjects about the differences between the training-sessions and the experimental task. The subjects were told that the e-mail that transferred from the detection screen to the allocation screen could in some cases be distorted. Subjects were also told that their knowledge with regard to the location of the threatened building was not always usable. Though a pattern always rightfully warned the subject about the type of building (whether it was a factory or an hospital) which could be on fire, the location could be different than would have been expected on the basis of the pattern.

The experimental task contained 16 scenarios, made up of 12 time periods of 15 seconds each. Each team or individual was presented with identical scenarios in a fixed order. The first four scenarios consisted of so called "routine scenarios". In these scenarios the e-mail was not distorted and the knowledge of the subjects concerning the patterns was always usable. The next four scenarios were also routine scenarios. In these scenarios, however, the e-mail was distorted. The following four scenarios contained so called "non-routine" with undistorted e-mail. The experimental task ended with four non-routine scenarios with distorted e-mail. The reason that scenarios were presented in a fixed order was that in this way subjects immediately could apply their newly learned knowledge about patterns without any limitations. If subjects were directly confronted with non-routine scenarios or scenarios with distorted e-mail, it might have discouraged subjects to use this knowledge. After all, in these scenarios the knowledge about patterns did not contribute to their performance. Because of this, there was a possibility that subjects in a later stage of the experimental task no longer used the knowledge about patterns, even if they eventually where presented with scenarios were this knowledge was applicable.

4.4 Design

Within subjects conditions

The distortion of the standardised e-mail was manipulated within subjects. All subjects were presented with 8 scenarios without distorted e-mail and 8 scenarios with distorted e-mail. Likewise, routine and non-routine scenarios were manipulated within subjects. All subjects were presented with 8 routine scenarios and 8 non-routine scenarios. In this way four "blocks" of scenarios were formed: two blocks of routine scenarios with and without distorted e-mail and two blocks of non-routine scenarios with and without distorted e-mail.

Between subjects conditions

1 *Individuals.* Individuals had to carry out both the detection as well as the allocation task. With a specially designed computer mouse they could control the features on the detection screen as well as the allocation screen.
2 *Unrestricted communication.* In these teams both the allocator and the observer were informed about patterns. Subjects were placed in the same room and communication took not only place via the standardised e-mail facilities, but also face-to-face.
3 *Restricted communication without shared knowledge.* In these teams only the allocator was informed about patterns. Subjects were physically separated and communication took place strictly via the standardised e-mail facilities.
4 *Restricted communication with shared knowledge.* In these teams both the allocator and the observer were informed about patterns. Subjects were physically separated and communication took place strictly via the standardised e-mail facilities.

4.5 Dependent variables

Manipulation check

In order to check whether subjects performed according to the instructions, a manipulation check was carried out on whether the observers searched for the correct type of building in the correct sector, after having interpreted the last building of the pattern.

Performance measures

The analysis of the fire-fighting paradigm described provided us with information concerning the critical time frames of the fire-fighting task. This information was used to establish objective performance measures of team functioning. The main performance measures were, first, whether the allocator had pulled back sufficient resources in time frame 8, and, second, whether in time frame 10 sufficient resources were allocated to either the hospital or the factory.

Timing of actions and communication of messages

In order to gain insight when subjects performed an action or sent each other messages with the e-mail the timing of actions and communication of messages was recorded. This was done for the critical time frames 7, 8, 9 and 10. Starting with the final building of the pattern, the processes of sending and reading messages and the start of actions were measured. The following variables were recorded:

1 Time at which observer sends last building of pattern to allocator.
2 Time at which allocator reads message about last building of pattern.
3 Time at which observer starts searching for threat message of factory or hospital.
4 Time at which observer sends threat message to allocator.
5 Time at which allocator reads threat message.

Observer-rating

During the experimental task a knowledgeable observer rated the verbal communication which took place between the subjects in the face-to-face condition. A specially designed form was used to rate the communication into different categories. The following categories were used:

- *Data communication.* Information about fires, the location, type of building, and the number of fire-units was rated as "data communication". There were distinct ratings for questions and answers.
- *Task communication.* This was rated into 6 subcategories. First, communication about the present actions members of a team were carrying out was rated as "logging". Second, when members of a team were correcting each others utterances, this was scored as "correction". Third, team members indicated their workload, this was scored as

"workload expression". Fourth, when team-members mentioned how well they performed, this was rated as "evaluation". Fifth, communication in order to agree upon a new division of tasks was rated as "task reallocation". Sixth, when one team-member told the other team-member without deliberation, which action he or she should carry out, this was rated as "task adaption".

- *Domain knowledge communication.* This category was used when members of a team spoke with each other about learned rules and strategies in order to improve their performance.
- *Meta-communication.* Communication involving communication was rated as "meta-communication".
- *Remaining communication.* Communication which was unclear of could not be rated in the existing categories (for example social talk) was rated as "remaining communication".

In addition to the above described categories communication control was also rated. This was rated for data communication, task communication and domain knowledge communication and consisted of utterances which indicated if a message was received and understood. Examples of these utterances are "okay" or "roger".

5 RESULTS

5.1 Relevant comparisons

In order to test the main hypotheses, three pairwise comparisons between the four groups were carried out:

1. In order to test whether the fire-fighting task was a true team task, the unrestricted communication condition was compared with the individual condition. The rationale behind this comparison was that both individuals as well as the team members of the unrestricted communication condition shared pattern knowledge and were unrestricted in their information exchange (under the assumption that individuals shared knowledge with themselves and communicated with themselves). The only difference between the two conditions, then, was that the individuals had to carry out certain crucial task elements in a serial fashion, whereas the teams could carry out these task elements in parallel.
2. In order to test the effect of unrestricted communication, the teams of the unrestricted communication condition and the teams of the restricted communication condition with shared knowledge were compared. In both groups, pattern knowledge was shared by the observers, the only difference being that the physically separated teams were restricted in their communication to task level information exchange (i.e., data communication), whereas the free communication group was unrestricted in its information exchange. Nevertheless, in both conditions teams had the possibility for an optimal performance.
3. In order to test the effect of shared knowledge, teams of the restricted communication conditions *with* shared knowledge and *without* shared knowledge were compared. In both

conditions communication took place via standardised e-mail and subjects were physically separated, the only difference being that the observers *without* shared knowledge did not have any pattern knowledge, whereas the observers *with* shared knowledge did have pattern knowledge.

5.2 Manipulation check

The results showed that all subjects, in all conditions, searched for the correct type of building, indicating that instructions were well-understood. In most cases subjects also searched in the correct sector (i.e., the one opposite to where the last building of the pattern started burning). Averaged across the 16 scenarios, the percentages of teams searching in the correct sector were 82% for the unrestricted communication condition, 88% for the restricted communication condition with shared knowledge, and 89% for the individuals. The remaining teams probably learned, in the non-routine conditions, to search in some sector other than the opposite one. This adaptive learning effect was apparent only in the final block of four scenarios (non-routine scenario and distorted e-mail). The observers in the restricted communication group *without* shared knowledge were dependent on the allocator for directions on where to search. In cases of e-mail breakdowns, the allocator did not perceive a pattern and, hence, could not direct the observer to a sector. Consistent with this manipulation, in this group only 64% of the observers searched in the correct sector, this percentage being higher in the non-distorted e-mail scenarios (76%) than in the distorted e-mail scenarios (51%).

We may conclude from these results that subjects acted according to instructions.

5.3 Performance measures

Time frame 8

Two main strategies could be discovered for assembling sufficient resources in time frame 8: the resources could either be pulled back from other buildings or they could be kept in reserve all the time (i.e., teams chose to let other buildings prior in the scenario burn down). The second strategy is clearly less optimal than the first, since buildings unnecessarily burn down. However, both strategies are better than the third alternative: not having sufficient resources available. For each scenario, each team was classified as performing in either of three categories: sufficient resources after pulling back, sufficient resources still available, and insufficient resources.

The results are shown in Figure 10. A loglinear model was fitted to the data. The best-fitting model only contained the variables "condition", "category of resource allocation", and the interaction between the two. The variable "block" (i.e., the within subjects manipulation), nor

any interaction with this term, was not significant. Hence, there were no effects of distorted e-mail or of non-routine scenarios.

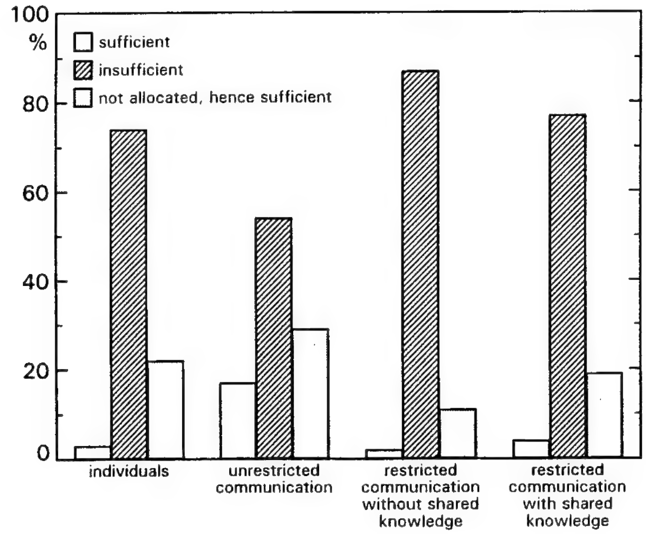

Fig. 10 Performance measurements during time frame 8.

There was a significant interaction when comparing the individuals with the unrestricted communication teams, $\chi^2(20)=52.79$, $p<.001$. Inspection of Figure 10 shows that this result is caused by the unrestricted communication group having assembled sufficient resources in more scenarios than the individuals (sufficient resources were assembled in time frame 8 by 46% of the unrestricted communicating teams versus 26% of the individuals). The interaction was also significant when comparing the unrestricted and the restricted communication groups (both with shared knowledge), $\chi^2(20)=47.98$, $p<.001$. Inspection of Figure 10 shows that this result is caused by the group with unrestricted communication having assembled sufficient resources in more scenarios than the group with restricted communication (sufficient resources were assembled in time frame 8 by 46% of the unrestricted communicating teams versus 23% of the restricted communication teams *with* shared knowledge). The interaction of condition by resource allocation was not significant when comparing the restricted communication groups *with* and *without* shared knowledge, $\chi^2(20)=23.26$, $p>.10$, indicating that in both groups the allocator was unable to assemble sufficient resources in time frame 8.

Time frame 10

In time frame 10, the large building (hospital or factory) started to burn. In order to be able to effectively fight this fire, the required number of resources needed to be present at the site of the large building at the start of time frame 10. Three categories could be distinguished: sufficient resources were available at the start of time frame 10, sufficient resources were available at the start of time frame 11 or 12 (the correct allocation was made, but it was too late), insufficient resources were available throughout time frames 10, 11 and 12.

The results are shown in Figure 11. A loglinear model was fitted to the data. The best-fitting model contained the variables "condition", "block", "category of resource allocation", and the 2-way interactions between condition and category and block and category. Neither the interaction between condition and block nor the three-way interaction between condition, block and category were significant.

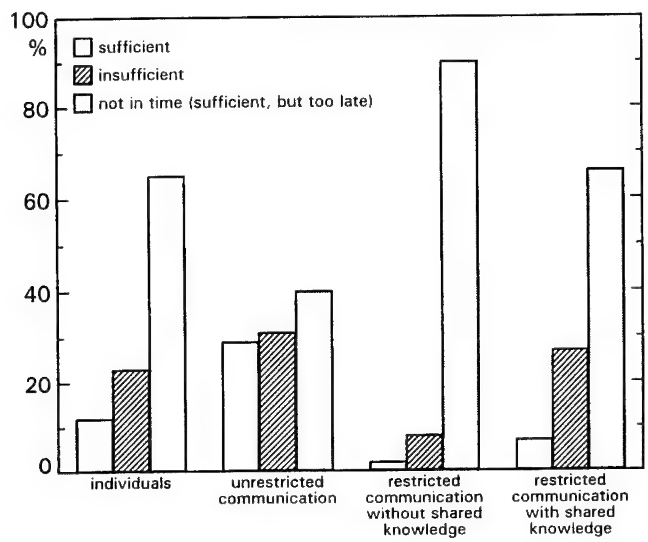

Fig. 11 Performance measurements during time frame 10.

There was a significant interaction when comparing the individuals with the unrestricted communication teams, $\chi^2(11)=35.37$, $p<.001$. Inspection of Figure 11 shows that this result is caused by the unrestricted communication group having allocated sufficient resources in more scenarios than the individuals (sufficient resources were allocated in time frame 10 by 29% of the unrestricted communicating teams versus 12% of the individuals). In addition, the individuals were more often too late than the unrestricted communication group (65% versus 40%, respectively). The interaction was also significant when comparing the unrestricted communication group and the restricted communication group (both with shared knowledge), $\chi^2(11)=41.19$, $p<.001$. Inspection of Figure 11 shows that this result is caused by the unrestricted communication group having allocated sufficient resources in more scenarios than the restricted communication group (sufficient resources were allocated in time frame 10 by 29% of the unrestricted communicating teams versus 7% of the restricted communicating teams). In addition, the restricted communication group was more often too late than the unrestricted communication group (66% versus 40%, respectively). The interaction of condition by resource allocation was significant when comparing the restricted communication groups *without* and *with* shared knowledge, $\chi^2(11)=38.19$, $p<.001$. Inspection of Figure 11 shows that when knowledge was shared, more frequently insufficient resources were available (8% in the restricted communication group *without* shared knowledge versus 27% *with* shared knowledge), whereas when knowledge was not shared, most often the allocation was made too late (90% *without* shared knowledge versus 66% in the restricted communication group *with* shared knowledge).

The interaction of block by resource allocation was significant across the four conditions, $\chi^2(33)=63.71$, $p=.001$. Figure 12 shows that this effect was largely caused by the transition from the first two routine blocks to the last two non-routine blocks. Compared with the routine scenarios, in the non-routine scenarios resources were more often allocated too late rather than in insufficient numbers. This is most likely due to the fact that observers had to search longer for the threat in the non-routine scenarios. This, in turn, led to a later transmission of the threat to the allocator who could only then assign resources to the threat.

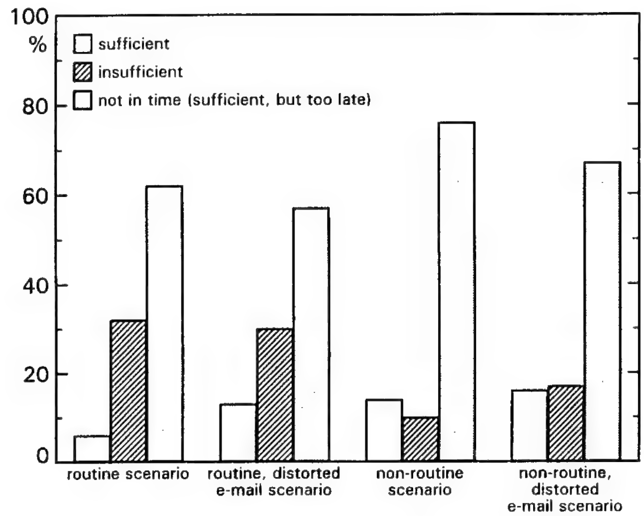

Fig. 12 Interaction block by resource.

5.4 Timing of actions and communication of messages

In some conditions, actions were not carried out or messages were not sent by all subjects. The repeated-measures analysis of variance was then carried out with missing data; in those cases where too many data were missing (and hence complete teams were omitted from the analysis), the four scenarios within one block were averaged, resulting in four measures for each team. Obviously, in the latter case no effects of type of scenario could be tested any more. Where possible, both approaches to missing data were taken simultaneously and the results were cross-checked. Where discrepancies arise, this will be noted in the text.

Sending and reading the last building of the pattern

On average, the last building of the pattern was sent after 105.81 s by the individuals, 106.58 s by the unrestricted communication group, 96.71 s by the restricted communication group *without* shared knowledge, and 100.32 s by the communication group *with* shared knowledge. Given the large number of missing cases particularly with the individuals, a repeated-measures analysis of variance was carried out on the block averages. The overall ANOVA across the four conditions was not significant, $F(3,36)=1.18$, $p=.33$, nor were any pairwise differences between the conditions significant. On average, the last building of the pattern was

read after 112.47 s by the individuals, 111.05 s by the unrestricted communication group, 101.97 s by the restricted communication group *without* shared knowledge, and 104.86 s by the restricted communication group *with* shared knowledge. Using block averages because of missing data, no significant differences were found, all $F\mathrm{s} < 1$.

Start of search for threat message

On average, the search for the threat message started after 102.51 s for the individuals, 94.76 s for the unrestricted communication group, 111.72 s for the restricted communication group *without* shared knowledge, and 98.77 s for the restricted communication *with* shared knowledge.

The overall difference among the four conditions was significant, $F(3,39)=10.56$, $p<.001$. Planned comparisons showed significant main effects of condition for the individuals and the unrestricted communication group, $F(1,20)=4.48$, $p=.05$, for the unrestricted communication and restricted communication *with* shared knowledge groups, $F(1,20)=11.02$, $p=.003$, and for the restricted communication groups *without* and *with* shared knowledge, $F(1,19)=26.85$, $p<.001$. The interaction between condition and type of scenario (routine versus non-routine scenarios) was significant only when comparing the restricted communication *without* and *with* shared knowledge groups, $F(1,19)=5.48$, $p=.03$. Inspection of the means indicated that the restricted communication group *without* shared knowledge actually started searching earlier for the threat message in the non-routine scenarios (routine: 115.39 s; non-routine: 108.06 s), whereas the restricted communication group *with* shared knowledge did not differ in both types of scenarios (routine: 99.01 s; non-routine: 98.53 s). This effect is probably caused by the initiative taken by the observers in the restricted communication group *without* shared knowledge to start searching for the threat message in the absence of any directions given by the allocator. This initiative could only be taken after some experience was built up with searching for threat messages. Given that the non-routine scenarios were always the final eight scenarios, this learning effect is inherently confounded with the effect of type of scenario. No significant interactions between condition and type of communication (normal versus disturbed) were found.

Sending and reading the threat message

On average, the threat message was sent by the observer after 111.10 s for the individuals, 107.80 s for the unrestricted communication group, 118.92 s for the restricted communication group *without* shared knowledge, and 111.44 s for the restricted communication group *with* shared knowledge. Planned comparisons on block averages revealed marginally significant differences between the individuals and the unrestricted communication group, $F(1,19)=3.24$, $p=.09$, the unrestricted communication group and the restricted communication group *with* shared knowledge, $F(1,20)=3.72$, $p=.07$and a significant difference between the restricted communication groups *with* and *without* shared knowledge, $F(1,14)=5.41$, $p=.04$. These data apply only to those cases where a threat message was in fact sent.

On average, the threat message was never sent in 17% of the cases for the individuals, 15% of the cases for the unrestricted communication group, 54% of the cases for the restricted communication group *without* shared knowledge, and 19% of the cases for the restricted communication group *with* shared knowledge. The relatively high percentage of cases that the threat message was never sent by the observers in the restricted communication group *without* shared knowledge can be explained by noting that in distorted e-mail scenarios the allocator never sees a pattern and hence can never instruct the observer to search for a threat message. The observer can only search on his or her own initiative, as a result of previous learning. Fig. 13 presents the search task for the four conditions graphically.

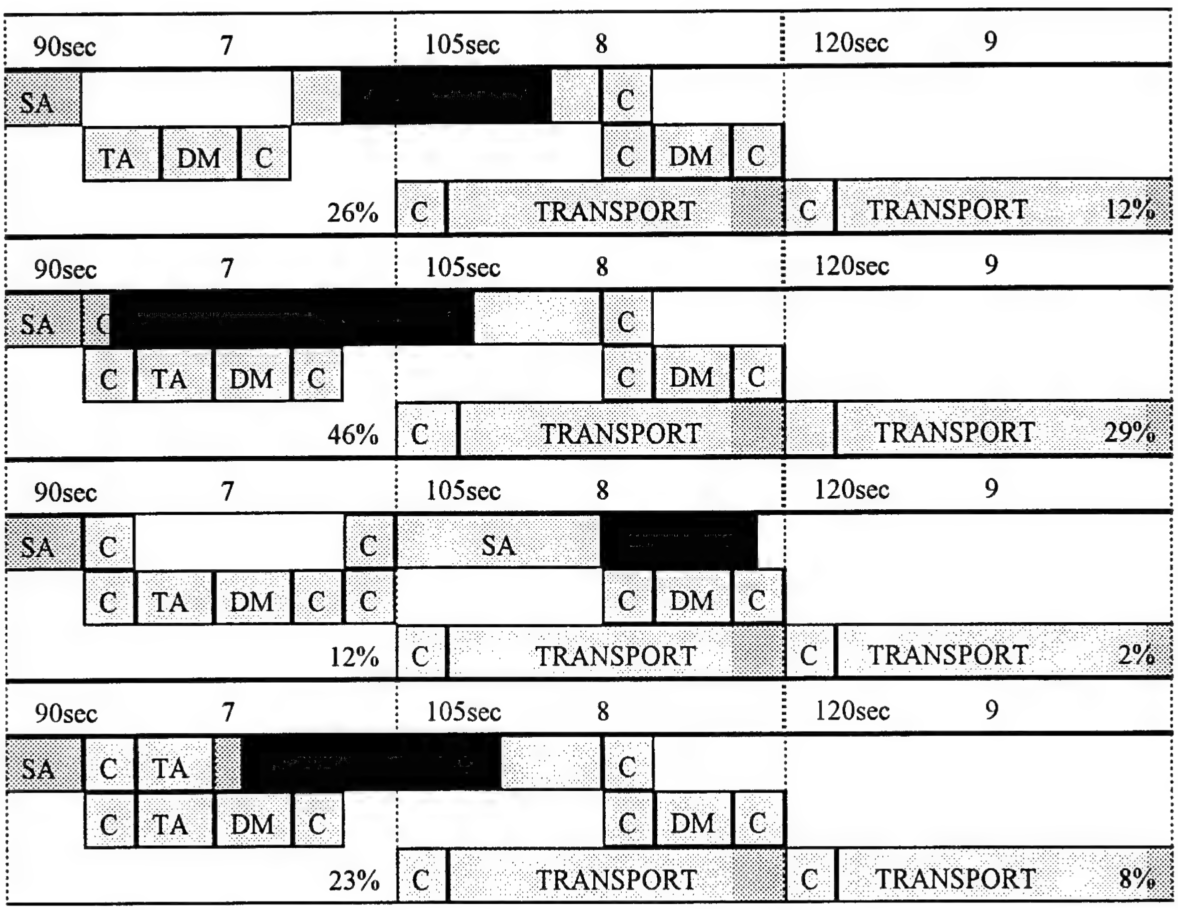

Fig. 13 Start and stop of the search task in the four conditions. The percentages denote the deadlines reached.

On average, the threat message, if sent, was read by the allocator after 117.12 s for the individuals, 113.91 s for the unrestricted communication group, 120.98 s for the restricted communication group *without* shared knowledge, and 115.77 s for the restricted communication group *with* shared knowledge. Planned comparisons showed no significant differences among these groups (individuals versus unrestricted communication group: $F(1,20)=1.08$, $p=.31$; unrestricted communication group versus restricted communication

group *with* shared knowledge: $F(1,20)<1$; restricted communication groups *without* versus *with* shared knowledge: $F(1,15)=1.00$, $p=.33$).

5.5 Observer rating

The communication which took place during the unrestricted communication condition was rated into the different categories as described in § 3.5. Table II gives an overview of the mean number of utterances per scenario for each category (the means are also divided in utterances during a scenario and between scenarios when subjects waited for the next scenario to start).

Table II Mean number of utterances per category during a scenario, between a scenario and total.

	during scenarios		between scenarios		total	
	mean	SD	mean	SD	mean	SD
total communication	24.21	10.38	2.67	2.26	26.88	11.10
total data communication	12.10	6.56			12.10	6.56
questions	1.87	2.36			1.88	2.36
answers	8.74	4.76			8.74	4.76
data communication control	1.49	1.54			1.49	1.54
total task communication	8.18	6.15	0.48	0.82	8.65	6.16
log	5.22	5.74			5.22	5.74
correction	0.45	0.86			0.45	0.86
workload	0.24	0.55	0.02	0.18	0.27	0.58
evaluation	0.52	0.93	0.38	0.67	0.90	1.14
task division	0.06	0.29	0.02	0.18	0.09	0.35
task overtake	1.26	1.64			1.26	1.64
task communication control	0.41	0.71	0.05	0.29	0.46	0.79
total domain knowledge communication	2.78	2.76	1.76	2.00	4.53	3.89
domain knowledge	2.32	2.17	1.33	1.42	3.65	2.97
domain knowledge comm. control	0.45	0.83	0.43	0.73	0.88	1.24
meta communication	0.39	0.70	0.14	0.61	0.53	0.99
remaining communication	0.77	1.09	0.30	0.68	1.07	1.40

The following conclusions can be drawn from table 5.1. First, communication took place both during and between scenarios but much more during than in between. Second, data communication, which only took place during scenarios, took the largest part of the total communication. Apparently, while data communication could perfectly take place via standardized e-mail, subjects felt the need to communicate this information directly to each other. Note that subjects gave each other more information than explicitly asked for (e.g., more answers were given then questions asked). Third, during scenarios, subjects communicated a great deal about the task itself. Most of this communication was logging. Subjects tended to tell each other continuously about the activities they were undertaking.

Fourth, during as well between scenarios, subjects were communicating about past actions and the strategies used in order to improve performance (domain knowledge communication).

Figures 14-16 give an overview of the relative contribution of each communication category to the total (including during and between scenarios as well as both).

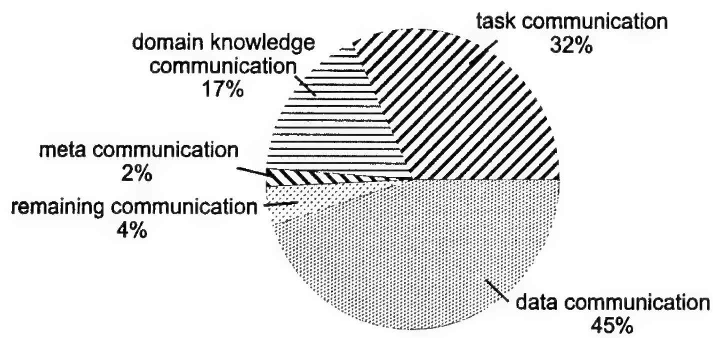

Fig. 14 Relative contribution of each communication category to the total during scenarios as well as between scenarios.

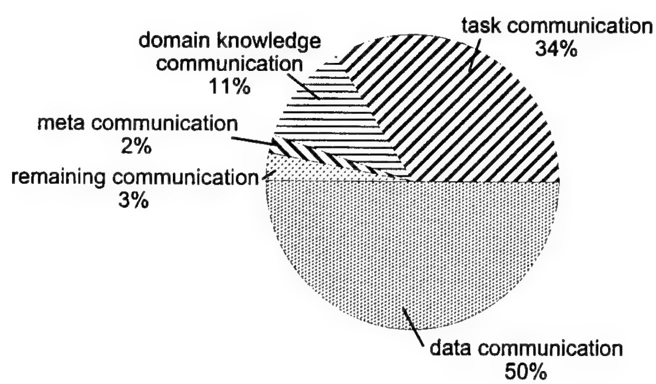

Fig. 15 Relative contribution of each communication category to the total during scenarios.

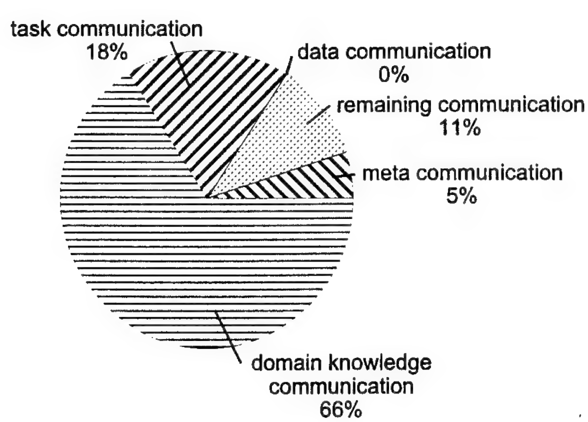

Fig. 16 Relative contribution of each communication category to the total between scenarios.

During the tasks, half of the information was about data needed for task execution. Approximately a third (34%) of the communication during tasks was about performing the task (task communication). Approximately a tenth (11%) of the communication was exchanging domain knowledge. The amount of meta-communication was small (2%), and so was the remaining communication (3%). Between the scenarios, the distribution of communication types was very different. Obviously, no data communication took place. Two-thirds of the communication was domain knowledge communication (66%), and one fifth was on performing the tasks (18%). Some remaining communication took place in 11% of the utterances, and the amount of meta-communication was, again, small (5%).

6 DISCUSSION

In this report, we started with describing a framework for knowledge and information use within teams, and continued with focusing on the necessity for working with more than one agent, the conditions of communication and coordination, and the distribution of knowledge within a team. The hypotheses, based on the framework and an extensive analysis of a command & control task, were tested experimentally. In this section we discuss the experimental results and how to continue this type of research.

6.1 Experimental results

Three comparisons were made in order to test the hypotheses stated in § 3.4. The first comparison was between individuals and teams that had unrestricted communication possibilities. The results show that forming a team of two agents (instead of doing the job alone) benefits the overall performance of the fire-fighting task. During the critical time period, teams had more fire-fighting units available than individuals. Consequently, more often sufficient units were allocated in the teams condition compared to the individual condition. Also, individuals were more often too late. The analysis of the fire-fighting task had already made clear that for effective execution, certain activities had to be performed in parallel. That individuals could not perform certain activities in parallel is also made clear by the fact that individuals were later than teams in searching for and sending the threat message. Since the results of the experiment support the conclusion that certain tasks had to be performed in parallel, we may state that the fire-fighting task is truly a team task.

The second comparison was made between teams that had unrestricted communication possibilities and teams that were restricted in their communication to data communication only. The a priori analysis of the fire-fighting task had already made clear that restricting communication to data does not necessarily lead to a performance decrease. In other words, data communication (via standardized e-mail) provides the same possibilities for effective task execution as unrestricted communication. However, the results show that teams with

unrestricted communication possibilities perform better than teams that have restricted communication possibilities. During the critical time period, unrestricted communication teams had more resources available than the restricted communication teams, and more often sufficient units were allocated. In addition, compared with the unrestricted communication teams, the restricted communication teams were more often too late with allocating units. Finally, the unrestricted communication group began earlier with searching for the threatened building than the restricted communication group, and they were earlier with sending a message about the threatened building, once found.

Apparently, restricting communication to data only leads to a performance decrease. Two explanations can be put forward for this result. A first explanation is that teams with unrestricted communication possibilities had more opportunities for coordination. The results of the observer rating seem to support this explanation. Besides data communication, most communication took place about the task. Subjects communicated a great deal about their task execution, and informed each other especially what activities they were doing on a particular moment (i.e., logging). This increased insight in the task performance of others, and in the consequences of one's own task performance for that of others, may have provided a better coordination in performing tasks.

An alternative explanation for the results is that in teams with unrestricted communication, more learning could have taken place to optimize the task. The need for optimization is indicated by the overall low performance in all conditions. Objectively, the time for reflection about the task, usually taking place at quiet moments after the critical period and between the scenarios, was equal in both conditions. However, it is known from the literature on cooperative learning (see e.g., Druckman & Bjork, 1994) that working together can be beneficial for co-workers. Our own results, showing that teams perform better than individuals, are consistent with a cooperative learning effect as an explanation. Further, when we look at the observational data in detail, the second most communication between the team members (besides data communication), after task communication, is about domain knowledge. This type of communication took place during as well as between scenarios, indicating that teams continuously monitor their previously used strategies, discuss and adjust them when necessary. This behaviour, which is also associated with the team self-correction phenomenon as described by Blickensderfer, Cannon-Bowers and Salas (in press), was absent in the restricted communication condition.

The third comparison was made between teams with restricted communication possibilities *without* and *with* shared knowledge. Sharing knowledge gives team members the possibility to act more independently of each other and substitute for each other's tasks when necessary. The task analysis shows that this can be profitable in the fire-fighting task. Therefore, it is assumed that sharing knowledge across team members contributes to the overall team performance. The results of the experiment support this assumption. Although both restricted communication teams had insufficient resources available as well as allocated, the teams *with* shared knowledge more often allocated insufficient resources, whereas the teams *without*

shared knowledge were too late with the allocation of resources in almost all cases. This result indicates that teams with shared knowledge were faster in allocating resources than teams without shared knowledge. Besides that, the shared knowledge group was also earlier in searching the threat message and sending the threat message. On basis of these results we may conclude that shared knowledge contributed to an increased performance of the restricted communication teams.

Summarized, the following three main conclusions can be drawn from the experimental results. First, the fire-fighting task truly is a team task because for optimal task performance, crucial task elements should be carried out in parallel. Second, communication restricted to data exchange only leads to team performance decrease. Unclear is whether this is caused by absent communication of domain knowledge needed for cooperative learning or team self correction, or due to absent communication of task information needed for coordination. Third, distributing knowledge over team members leads to an increase of parallel task execution and to better team performance.

6.2 Further research

We do not know yet which mechanisms underlies the beneficial effects of unrestricted communication: learning, communicating coordination information, or both. These two factors will be the topic of our future research. There has been done already research on this matter (e.g., Fussell & Benimoff, 1995), but in contrast to others that focus on a communication perspective, our research is carried out from a task perspective. In the next experiment, also taking place in the fire-fighting paradigm, team members will be separated in order to prevent cooperative learning, and communication will be restricted. In some of the separated teams, coordination related information will be communicated too by means of a dynamic visualization of the task dependencies between the agents. It is hypothesized that exchanging coordination information improves team performance. In theory, the experiment could be done with teams communicating without restrictions, but in practice, it will be difficult to prevent subjects from communicating information for learning during task execution.

The results of our experiments in the fire-fighting paradigm seem generalizable to teams performing other tasks, such as command & control. The fire-fighting task has been decomposed into four tasks: Situation Awareness, Threat Assessment, Decision Making/ Planning, and Direction & Control. The same decomposition can be used for other team tasks, such as Command & Control. As was shown in Figure 5, both the tasks and the types of knowledge are formulated in a generic way (i.e., when Fire Data is replaced by Data). However, in command & control, the tasks are usually divided over more than one domain. Because different domain experts can hold different viewpoints of a situation, conflicts between the domains can arise within the same function. For improving generalizability

further, the paradigm should enable the occurrence of domain conflicts. Then, command & control teams solving domain conflicts can be studied as well.

Another restriction of the fire-fighting domain, as it has been realized in the experiments, is the level of uncertainty in the information used for performing the tasks. Two types of uncertainty can be distinguished: uncertainty of situational data (in the situation assessment task), and uncertainty on the patterns that indicate a threat (in the threat assessment task). In contrast to real-world settings, the level of uncertainty in the current paradigm was low. Further research may involve experiments with higher levels of uncertainty of both kinds. An associated aspect is the distinction between handling routine and non-routine situations. In the experiments, the non-routine scenarios we used could be solved with routine behaviour. The only difference was that the surveillance task, consisting of searching, was carried out over a longer period of time. Real non-routine scenarios demand knowledge-based problem solving. How teams will handle these kinds of scenarios needs to be investigated as well (cf. Cohen, 1993).

Further, we carried out the experiment with two types of team organization: a single agent and a team. Several other types of team organization could be the object of research. The organization of a team can be based on domains, on problem solving expertise (e.g., a division in scepticism, critics, and proposers; see Kornfeld & Hewitt, 1981), on function, on control role (supervision, execution, etc.). So, for a particular team size (say 3 members), different team organizations may be compared that deal with exactly the same environmental events. The role of various aspects can be investigated in this way. For example, in some forms of organization, face-to-face contact may be essential, while in others this may not be the case (especially where no negotiation takes place). See, for example, Williams (1977); Werkhoven, Punte and Spoelma (in press). Another question that may be investigated is the optimal size and structure of a team. Subquestions are: assuming that team members need a mental model of each colleague, how many models can they handle? To what extent does this depend on the differences in roles of the team member?

A final topic for further research is how to measure team performance. Team performance is not measured easily. A difficulty is that much team behaviour is covert and implicit while only overt and explicit behaviour can be measured. Common performance measures are correct task completion, and the amount of time consumed. Two problems exist with measuring correct task completion. First, correct task completion is often difficult to determine due to a lack of a gold standard definition. Second, often the task is made up of several sub-tasks and the result of some tasks may depend on the outcome of others. These sub-tasks can be rated as well. Consider a soccer-team: a coordinated action with two players to pass by an opponent may be appreciated equally well by the supporters as perhaps a lucky goal that may follow. In other words, enabling the conditions for success can be rated as well, especially when the result depends partially on chance. Further, not only task performance itself but also the gain of a correct task performance can be taken into account. In addition, the errors that are made during (sub)task performance (and the associated costs) can be taken

as a measure. Rouse et al. (1992) use an analysis method for human errors. Errors with clear consequences are important, but also errors that increase the probability of serious consequences, even when the final result may be positive.

The second common performance measure, time consumption, can be measured in terms of time taken to carry out a job, but also in terms of reaching deadlines. Especially in teams, in which the teams wait for a critical situation to occur, performing a job as quickly as possible is not important, as long as they can perform a job under critical circumstances within time; they cannot increase their productivity by speeding up their tasks (except that more time may become available for task evaluation, training, and relaxation.)

In short, what is needed for research on team decision making is an instrument for measuring shared capacity optimization.

6.3 Conclusions

In conclusion, we have contributed to the understanding of how to distinguish an expert team from a team of experts. We have found that well-performing teams do more than working separately, only communicating the results of their actions. Teams also need to communicate additional information, probably information such as knowledge they own or have learned and, in order to enhance coordination, information about what they are doing. Especially in our current society, in which more and more often people are enabled or forced to work together but distributed in time and place, the role of communication and coordination deserves considerable attention.

REFERENCES

Adams, M.B. (1995). Functional Analysis/Decomposition of Closed-loop, Real-time Work Processes. *Proceedings of the AGARD Mission System Panel,* 1-10.

Blickensderfer, E.L., Cannon-Bower, J.A. & Salas, E. (in press). Fostering Shared Mental Models through Team Self-Correction: Theoretical Bases and Propositions. In D. Johnson & S. Beyerlein (Eds.), *Advances in Interdisciplinary Studies in Work Teams series* (vol. 4). Greenwich, CT: JAI Press, Inc.

Boer, L.C. (1996). Losing Task Situation Awareness. *Paper presented at the 2nd Automation Technology and Human Performance Conference.* April: Cocoa Beach FL, USA.

Cannon-Bowers, J.A., Salas, E., & Converse, S.A. (1993). Shared Mental Models in Expert Team Decision Making. In N.J. Castellan jr. (Ed.), *Individual and Group Decision Making: Current Issues* (pp.221-246). Hillsdale, NJ: Lawrence Erlbaum Associates.

Chandrasekaran, B. (1987). Towards a functional architecture for intelligence based on generic information processing tasks. *Proceedings of the 10th IJCAI,* 1183-1192.

Chapanis, A., Parrish, R.N., Ochsman, R.B. & Weeks, G.D. (1977). Studies in interactive communication II. The effects of four communication modes on the linguistic performance of teams during cooperative problem solving. *Human Factors, 19,* 101-126.

Chou, C.D., Madhavan, D. & Funk, K. (1996). Studies of Cockpit Task Management Errors. *The International Journal of Avation Psychology, 6 (4),* 307-320.

Clancey, W.J. (1985). Heuristic classification. *Artificial Intelligence, 27,* 289-350.

Clark, A. (1996). A theoretical Model of Cooperation. *Proceedings of the 2nd International Conference on the Design of Cooperative Systems,* 57-82.

Cohen, M.S. (1993). Three Paradigms for Viewing Decision Biases. In G.A. Klein, J. Orasanu, R. Calderwood, & C.E. Zsambok (Eds.) *Decision Making in Action: models and methods* (pp. 36-99). Norwood, NJ: Ablex Publishing Corporation.

Converse, S.A., Cannon-Bowers J.A. & Salas, E. (1991). Team Member Shared Mental Models: a theory and some methodological issues. *Proceedings of the Human Factors Society 35th annual meeting,* 1417-1421.

Cremers, A.H.M. (1996). *Reference to Objects: an emperically based study of task-oriented dialogues.* Phd. thesis, Eindhoven, NL: IPO Institute for Perception Research.

Druckman, D. & Bjork, R.A. (1994). *Learning, remembering, believing: enhancing human performance.* Washington, DC: National Academy Press.

Dyer, J.L. (1984). Team Research and Team Training: a state of the art review. In F.A. Muckler (Ed.), *Human Factors Review* (pp.285-323). Santa Monica: The Human Factors Society.

Fussell, S.R. & Benimoff, N.I. (1995). Social and Cognitive Processes in Interpersonal Communication: Implications for Advanced Telecommunications Technologies. *Human Factors, 37,* 228-250.

Hollingshead, A.B. & McGrath, J.E. (1995). Computer-assisted Groups: A crititical Review of Empirical Research. In I.L. Goldstein (Ed.), *Frontiers of Industral and Organizational Psychology* (pp.46-78). San Francisco: Jossey-Bass Inc.

Klein, G.A. (1993). A Recognition-Primed Decision Model of Rapid Decision Making. In G.A. Klein, J. Orasanu, R. Calderwood & C.E. Zsambok (Eds.), *Decision Making in Action: models and methods* (pp.138-147). Norwood, NJ: Ablex Publishing Corporation.

Klein, G.A. (1997). An Overview of Naturalistic Decision Making Applications. In C.E. Zsambok & G.A. Klein (Eds.), *Naturalistic Decision Making* (pp.49-59). Mahwah, NJ: Lawrence Erlbaum Associates, Publishers.

Kornfeld, W.A. & Hewitt, C.E. (1981). The scientific community metaphor. *IEEE Transactions on Systems, Man, and Cybernetics, 11,* 24-33.

Lin, Z. & Carley, K. (1992). *Maydays and Murphies: a study of the effect of organizational design, task, stress on organizational performance* (Technical Report No. UPITT/LRDC/ONR-HGD-2). Pittsburg, PA: Carnegie Mellon University.

Mintzberg, H. (1983). *Structure in Lives: Designing Effective Organisations*. London: Prentice-Hall International Editions.

Orasanu, J. (1993). Decision Making in the Cockpit. In E.L. Wiener, B.G. Kanki & R.L. Helmreich (Eds.), *Cockpit Resource Management* (pp.132-172). San Diego, CA: Academic Press.

Orasanu, J. & Connolly, T. (1993). The Reinvention of Decision Making. In G.A. Klein, J. Orasanu, R. Calderwood & C.E. Zsambok (Eds.), *Decision Making in Action: models and methods* (pp.3-20). Norwood, NJ: Ablex Publishing Corporation.

Orasanu, J. & Salas, E. (1993). Team Decision Making in Complex Environments. In G.A. Klein, J. Orasanu, R. Calderwood & C.E. Zsambok (Eds.), *Decision Making in Action: models and methods* (pp.327-345). Norwood, NJ: Ablex Publishing Corporation.

Post, W.M., De Hoog, R., Wielinga, B.J. & Schreiber, A.T.H. (in press). Organizational Modelling with Commonkads: the Emergency Medical Service. *IEEE Expert.*

Rasmussen, J. (1983). Skills, rules and knowledge; signals, signs and symbols and other distinctions in human perfomance models. *IEEE Transactions on Systems, Man and Cybernetics, 13,* 311-333.

Rasmussen, J. (1993). Deciding an Doing: Decision Making in Natural Contexts. In G.A. Klein, J. Orasanu, R. Calderwood & C.E. Zsambok (Eds.), *Decision Making in Action: models and methods* (pp.158-171). Norwood, NJ: Ablex Publishing Corporation.

Rouse, W.B. & Morris, N.M. (1986). On Looking into the Black Box: prospects and limits in the search for mental models. *Psychological Bulletin, 100,* 359-363.

Rouse, W.B., Cannon-Bowers, J.A. & Salas, E. (1992). The Role of Mental Models in Team Performance in Complex Systems. *IEEE Transactions on Systems, Man, and Cybernetics, 22,* 1296-1308.

Salas, E., Bowers, C.A. & Cannon-Bowers, J.A. (1995). Military Team Research: ten years of progress. *Military Psychology, 7,* 55-75.

Schaafstal, A.M. & Bots, M.J. (1997). *Het effect van drie verschillende methoden voor cross-training op het presteren van teams* [The impact of three different methods for cross training on team performance] (Report TM-97-B001). Soesterberg, NL: TNO Human Factors Research Institute.

Salas, E., Dickenson, T.L., Converse, S.A. & Tannenbaum, S.I. (1992). Toward a Understanding of Team Performance and Training. In W. Swezey & E. Salas (Eds.), *Teams: their Training and Performance* (pp.3-29). Norwood, NJ: Ablex Publishing Corporation.

Schraagen, J.M.C. (1995). *Besluitvorming in teams: een onderzoeksparadigma* [Team Decision Making: a research paradigm] (Report TNO-TM 1995 B-1). Soesterberg, NL: TNO Human Factors Research Institute.

Schraagen, J.M.C. & Koster, E.R. (1996). *Het effect van gemeenschappelijke kennis op teambesluitvorming in een Command & Control taak* [The effect of shared knowledge on team decision making in a Command and Control task] (Report TM-96-B015). Soesterberg, NL: TNO Human Factors Research Institute.

Schraagen, J.M.C. & Rasker, P.C. (1996). *De invloed van training in elkaars taken op de besluitvorming van teams* [The Impact of Cross-training on Team Desicion Making] (Report TM-96-B013). Soesterberg, NL: TNO Human Factors Research Institute.

Serfaty, D., Entin, E.E. & Volpe, C. (1993). Adaption to stress in team decision-making and coordination. *Proceedings of the Human Facors and Ergonomics Society 37th Annual Meeting,* 1228-1232.

Stout, R. & Salas, E. (1993). The Role of Planning in Coordinated Team Decision Making: Implications for Training. *Proceedings of the Human Factors Society 37th annual meeting,* 1238-1242.

Stout, R. & Salas, E. (1993). The Role of Planning in Coordinated Team Decision Making: Implications for Training. *Proceedings of the Human Factors Society 37th annual meeting,* 1238-1242.

Tang, J.C. (1991). Findings from observational studies of collaborative work. *International Journal of Man Machine Studies, 14,* 143-160.

Urban, J.M., Bowers, C.A., Monday, S.D., & Morgan, B.B. jr. (1995). Workload, Team Structure, and Communication in Team Performance. *Military Psychology, 7,* 123-139.

Van de Velde, W. & Perram, J.W. (Eds.) (1996). *Agents Breaking Away.* Berlin/Heidelberg: Springer Verlag

Van Delft, J.H. & Schuffel, H. (Eds.) (1995). *Human Factors onderzoek voor toekomstige Commando Centrale KM* [Human Factors Research for future operations rooms Royal Netherlands Navy] (Report TNO-TM 1995 A-19). Soesterberg, NL: TNO Human Factors Research Institute.

Van Duin, M.J. & Rosenthal, U. (1996). *De Hercules ramp: individuen, organisaties en systemen* [Disaster of the Hercules: individuals, organisations and systems]. Crisis Onderzoeks Team, Rijks Universiteit Leiden/Erasmus Universiteit Rotterdam.

Van Heijst, G., Lanzola, G., Schreiber, A.T. & Stefanelli, M. (1994). Foundations for a methodology for medical KBS development. *Knowledge Acquisition, 6,* 395-434.

Volpe, C.E., Cannon-Bowers, J.E., Salas, E., & Spector, P.E. (1996). The Impact of Cross-Training on Team Functioning: An Empirical Investigation. *Human Factors, 38,* 87-100.

Wærn, A. & Gala, S. (1993). *The commonkads agent model* (Technical report Esprit Project 5248 KADS-II/M4/SICS/TR005/V.2.0), Swedish Institute of Computer Science.

Whittaker, S., Geelhoed, E. & Robinson, E. (1993). Shared Workspaces: how do they work and when are they useful? *International Journal of Man Machine Studies*, 813-842.

Wickens, C.D. (1992). *Human Engineering Psychology and Human Performance.* New York: HarperCollins Publishers Inc.

Wielinga, B.J. & Breuker, J.A. (1986). Models of expertise. *Proceedings ECAI-86,* 306-318.

Williams, E. (1977). Experimental comparison of face-to-face and mediated communication: a review. *Psychological Bulletin, 5,* 963-976.

Werkhoven, P.J., Punte, P.A.J. & Spoelma, E. (in press). *Seeing is Believing: Communication Performance under Isotropic Teleconferencing Conditions* (TNO Report), Soesterberg, NL: TNO Human Factors Research Institute.

Zachary, W.W., Zaklad, A.L., Hicinbothom, J.H. & Ryder, J.M. (1993). Cognet representation of tactical decision-making in anti-air warfare. *Proceedings of the Human Factors & Ergonomic Society 37th annual meeting.*

Zsambok, C.E. (1997). Naturalistic Decision Making Research and Improving Team Decision Making. In C.E. Zsambok & G.A. Klein (Eds.), *Naturalistic Decision Making* (pp.111-120). Mahwah NJ: Lawrence Erlbaum Associates, Publishers.

Soesterberg, 13 May 1997

Dr. W.M. Post
(First author)

Dr. J.M.C. Schraagen
(Project leader)

REPORT DOCUMENTATION PAGE

1.	DEFENSE REPORT NO. TD 97-0203	2.	RECIPIENT ACCESSION NO.	3.	PERFORMING ORGANIZATION REPORT NO. TM-97-B004
4.	PROJECT/TASK/WORK UNIT NO. 787.2	5.	CONTRACT NO. B97-021	6.	REPORT DATE 13 May 1997
7.	NUMBER OF PAGES 53	8.	NUMBER OF REFERENCES 52	9.	TYPE OF REPORT AND DATES COVERED Interim

10. TITLE AND SUBTITLE

The role of communication and coordination in team decision making in a command & control task

11. AUTHOR(S)

W.M. Post, P.C. Rasker and J.M.C. Schraagen

12. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

TNO Human Factors Research Institute
Kampweg 5
3769 DE SOESTERBERG

13. SPONSORING AGENCY NAME(S) AND ADDRESS(ES)

Director of TNO Human Factors Research Institute
Kampweg 5
3769 DE SOESTERBERG

14. SUPPLEMENTARY NOTES

15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTES))

In this study, the role of communication and coordination in team decision making in a command and control task has been investigated. First, a framework has been developed in which all team-related entities are described. Next, we have developed an artificial world in which various events take place. This world is represented by a city consisting of various buildings in which citizens live. The events are series of fires. A fire-fighting organization has been set up to deal with this situation. This organization has to allocate a restricted amount of resources to fulfill its goal: to rescue as many lives as possible.
Focus of research is on how to organize and support a team that observes the world and allocates the resources. These tasks have been analysed and a normative task structure has been described as a basis for performance measurements. Two experiments have been carried out. First, the hypothesis was tested that an experimental task (fire fighting) could not be carried out alone. Second, it was investigated whether teams that are restricted in their communication and coordination possibilities could perform as well as teams that can communicate and coordinate without restrictions. A third research topic was the role of distributing knowledge among the task performers.
The following three main conclusions can be drawn from the experimental results. First, the fire-fighting task truly is a team task because for optimal task performance, crucial task elements should be carried out in parallel. Second, communication restricted to data exchange only leads to team performance decrease. Third, distributing knowledge over team members leads to an increase of parallel task execution and to better team performance. Finally, we have observed that when team members can communicate without restrictions, much knowledge and information about the task is exchanged, both during and between the execution of tasks.

16.	DESCRIPTORS Command & Control Communication Coordination Task Analysis Team Decision Making		IDENTIFIERS

17a.	SECURITY CLASSIFICATION (OF REPORT)	17b.	SECURITY CLASSIFICATION (OF PAGE)	17c.	SECURITY CLASSIFICATION (OF ABSTRACT)
18.	DISTRIBUTION AVAILABILITY STATEMENT Unlimited availability			17d.	SECURITY CLASSIFICATION (OF TITLES)

VERZENDLIJST

1.	Directeur M&P DO
2.	Directie Wetenschappelijk Onderzoek en Ontwikkeling Defensie
3. {	Hoofd Wetenschappelijk Onderzoek KL Plv. Hoofd Wetenschappelijk Onderzoek KL
4.	Hoofd Wetenschappelijk Onderzoek KLu
5. {	Hoofd Wetenschappelijk Onderzoek KM Plv. Hoofd Wetenschappelijk Onderzoek KM
6, 7 en 8.	Bibliotheek KMA, Breda